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ROUNDNESS AND SHAPE OF MISSISSIPPI RIVER SANDS

R. DANA RUSSELL AND RALPH E. TAYLOR
Louisiana State University

ABSTRACT

Sands collected from the bed of the Mississippi River at intervals between Cairo, Illinois, and the Gulf of Mexico show no evidence of becoming rounded as a result of attrition during transportation. On the contrary, the larger sand grains become slightly more angular downstream. This effect seems to be chiefly due to chipping and fracturing of the grains. Sorting on the basis of shape appears to be a relatively unimportant factor in bed load transportation by the river, at least with respect to the sand sizes.

INTRODUCTION

"Streams characteristically round the pebbles and sands transported if the size is no smaller than about 0.05 mm."[1] This statement from one of the most recently published texts on petrology appears to represent the views of most geologists with respect to the effects of attrition during stream transportation. Natural conditions, however, are not so simple as this overgeneralized statement would lead one to believe. As far as the sand sizes are concerned, it is extremely doubtful whether streams "characteristically" round the grains. In streams of high gradient and velocity conditions of attrition probably are so rigorous that fracturing and chipping produce an increase in angularity of the grains rather than rounding them.

[1] F. F. Grout, *Petrography and Petrology* (New York: McGraw-Hill Book Co., 1932), p. 315.

In fact, it has been reported[2] that in the Salzach River of the Austrian Alps even the pebbles are reduced in size chiefly by fracturing, with the result that at least 88 per cent of them consist of angular blocks.

Even assuming that stream action is capable of rounding sand grains, the question of the amount of transportation necessary to produce rounded grains remains undetermined. Experiments indicate that sand must be transported for a very considerable distance before rounded grains will be formed. Anderson states that ". . . . it does not appear likely that sand grains in a single journey from the central part of the continent to the sea would experience sufficient wear to become rounded."[3]

The lower Mississippi River, with an average gradient of about three-tenths of a foot per mile between Cairo, Illinois, and the Gulf of Mexico,[4] appears to furnish an example of a major stream in which conditions of attrition should be sufficiently gentle to round sand grains if this action occurs in streams. In order to determine whether the Mississippi rounds the sand constituents of its bed load, the writers have made detailed studies of samples collected from the bed of the river at intervals between Cairo and the Gulf. Grain shapes, expressed by means of Wadell sphericity values,[5] have also been determined for some samples in an attempt to discover whether a progressive sorting on the basis of shape exists in the river. Although the number of samples analyzed is limited, it is believed that the

[2] Eberhard Fugger and Karl Kastner, "Die Geschiebe der Salzach (Geschiebe des Donaugebietes, 1., Donau-Studien nach dem Plane und den Instructionen von Dr. Jos. Ritter v. Lorenz-Liburnau, Dritte Abhandlung)," *Mitteilungen der k. k. geographischen Gesellschaft in Wien*, Beil. Band XXXVIII (1895).

[3] G. E. Anderson, "Experiments on the Rate of Wear of Sand Grains," *Jour. Geol.*, Vol. XXXIV (1926), p. 157.

[4] Owing to the highly irregular configuration of the bed, data on the slope of the latter are difficult to secure. The above figure is based upon the longitudinal bank slope and the hydraulic slope at high water. The slope, of course, progressively decreases downstream, being about 0.43 foot per mile immediately below Cairo and in the neighborhood of 0.15 foot per mile below New Orleans (see D. O. Elliot, *The Improvement of the Lower Mississippi River for Flood Control and Navigation* [U.S. Waterways Exper. Sta., Miss. River Comm., 1932], pp. 37 and 82).

[5] H. Wadell, "Volume, Shape, and Roundness of Quartz Particles," *Jour. Geol.*, Vol. XLIII (1935), pp. 250–80.

data secured yield definite evidence with regard to the effects of transportation by major streams like the Mississippi upon the physical characteristics of the transported sands.

REVIEW OF LITERATURE

The roundness, shape, and surface features of sand grains have been of interest to students of sedimentation from the time that sediments were first studied in detail. This phase of sedimentational analysis, however, has received much less attention than have the mineralogical makeup and the size distribution of sands. Until recently, geologists have been content with theoretical considerations, although occasional experiments were carried out.

Daubrée[6] probably was the first to conduct experiments on the resistance of sand grains to abrasion during transportation. He subjected different types of rock particles of sand size to wear in water-filled revolving cylinders and found the rate of wear to be very low. He reported in addition that particles smaller than 0.1 mm. in diameter could not be rounded in water. Experiments of similar nature carried out by Thoulet, Galloway, Anderson, and others[7] have substantiated Daubrée's findings that the wear of sand grains takes place slowly. With regard to the lower limit of rounding, Galloway concluded that particles as small as 0.05 mm. in diameter could be rounded by abrasion in water.[8]

In contrast to the results of these workers, Wentworth, Marshall, and others[9] have conducted experiments on the rate of wear of rock

[6] A. Daubrée, *Etudes synthétiques de géologie expérimentale* (Paris, 1879).

[7] J. Thoulet, "Sur la marche des sables de long des rivages," *Comp. rend. acad. sci., Paris*, Vol. CXLIV (1907), pp. 938–40; J. J. Galloway, "The Rounding of Grains of Sand by Solution," *Amer. Jour. Sci.*, Vol. CXCVII (1919), pp. 270–80; Anderson, *op. cit.;* E. J. Lovegrove, J. A. Howe, and Sir John Fleet, "Attrition Tests of British Road-Stones," *Mem. Geol. Surv. Great Britain* (1929).

[8] Galloway, *op. cit.*, p. 270.

[9] C. K. Wentworth, "A Laboratory and Field Study of Cobble Abrasion," *Jour. Geol.*, Vol. XXVII (1919), pp. 507–21; P. Marshall, "The Wearing of Beach Gravels," *Trans. New Zealand Inst.*, Vol. LVIII (1927), pp. 507–32; Fred W. Freise, "Untersuchung von Mineralen auf Abnutzbarkeit bei Verfrachtung im Wasser," *Min. und Pet. Mitt.*, Vol. XLI (new ser., 1931), pp. 1–7; A. B. Cozzens, "Rates of Wear of Common Minerals," *Wash. Univ. Studies, Sci. and Tech.*, No. 5 (new ser., 1931), pp. 71–80; F. Düll, "Das Gesetz des Geschiebeabriebes," *Mitteilungen aus dem Gebiete des Wasserbaues und der Baugrundforschung*, Heft 1 (Berlin: W. Ernst & Sohn, 1930); A. Schok-

particles which have been interpreted as indicating that sand grains are worn comparatively rapidly. It is well to note with regard to these last experiments that particles larger than sand sizes were used; hence any conclusions pertaining to sand grains which are based upon these data are open to question. Several investigators[10] have pointed out that, even within the range of sand sizes, the larger grains usually show better rounding and presumably are worn more rapidly.

The same criticism applies to studies of the effects of attrition in natural streams. All investigations of this type,[11] as far as the writers are aware, have been confined to particles of pebble size or larger. That pebbles usually become rounded by attrition in streams seems fairly well established; it does not follow, however, that sand grains are also rounded.

In most of these studies, both field and experimental, no attempt seems to have been made to define carefully the term "roundness." As a result, the data obtained by different workers are subject to a considerable range of interpretation. This same difficulty is encountered in the work of Sorby, Phillips, Mackie, Goodchild, Retgers, Sherzer,[12] and others who have attempted to interpret the

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litsch, *Über Schleppkraft und Geschiebebewegung* (Leipzig: W. Engelmann, 1914) and "Über die Verkleinerung der Geschiebe in Flussläufen," *Sitzungsberichte der Akad. der Wissenschaften in Wien, Mathem.-naturw. Kl.*, Band CXLII, Abt. IIa (1933), pp. 343–66.

[10] H. C. Sorby, "On the Structure and Origin of the Non-calcareous Stratified Rocks," *Quart. Jour. Geol. Soc.*, Vol. XXXVI Proc. (1880), pp. 46–92; G. R. MacCarthy, "The Rounding of Beach Sands," *Amer. Jour. Sci.*, Vol. CCXXV (1933), pp. 205–24, and "Eolian Sands: A Comparison," *ibid.*, Vol. CCXXX (1935), pp. 81–95; Theresia Guggenmoos, "Über Korngrössen- und Kornformenverteilung von Sanden . . . . ," *Neues Jahrbuch für Min. Geol. und Paleon.*, Beil. Band LXXII, Abt. B (1934), pp. 429–87; Wadell, *op. cit.;* Marshall, *op. cit.*

[11] E. Fugger and K. Kastner, *op. cit.;* C. K. Wentworth, "A Field Study of the Shapes of River Pebbles," *U.S. Geol. Surv. Bull. 730* (1922), pp. 103–14; Schoklitsch ("Über die Verkleinerung der Geschiebe in Flussläufen," *loc. cit.*) summarizes other studies of European geologists and hydraulic engineers.

[12] Sorby, *op. cit.;* J. A. Phillips, "On the Constitution and History of Grits and Sandstones," *Quart. Jour. Geol. Soc.*, Vol. XXXVII (1881), pp. 6–28; William Mackie, "The Sands and Sandstones of Eastern Moray," *Trans. Edin. Geol. Soc.*, Vol. VII (1893–98), pp. 148–72, and "On the Laws That Govern the Rounding of Particles of Sand," *ibid.*, Vol. VII (1893–98), pp. 298–311; J. G. Goodchild, "Desert Conditions in

history of sediments on the basis of a qualitative consideration of the physical properties of their constituent particles. Even the much-quoted laws of rounding formulated by Mackie[13] fail to define roundness and constitute simply an incomplete expression for the resistance of mineral particles to abrasion.

A number of studies have been made in which grains have been grouped into arbitrarily limited roundness classes in order to establish a basis of comparison and to obtain an expression of degree of roundness.[14] This method is open to the criticism that its application involves the element of personal judgment. To eliminate this disadvantage various attempts have been made to express numerically the degree of roundness of the individual grains.

Wentworth, after studying pebble abrasion experimentally and in streams, expressed roundness as a ratio of the radius of curvature of the sharpest developed edge to the mean radius of the particle.[15]

Britain . . . .," *ibid.*, Vol. VII (1893–98), pp. 203–22; J. W. Retgers, "Über die Mineralogische und Chemische Zusammensetzung der Dünensands Hollande," *Neues Jahrbuch für Min.*, Vol. I (1895), pp. 16–74; W. H. Sherzer, "Criteria for the Recognition of the Various Types of Sand Grains," *Geol. Soc. Amer. Bull. 21* (1910), pp. 625–62.

[13] "On the Laws That Govern the Rounding of Particles of Sand," *loc. cit.*

[14] Mackie, "On the Laws That Govern the Rounding of Particles of Sand," *loc. cit.*, D. Dale Condit, "The Petrographic Character of Ohio Sands with Relation to Their Origin," *Jour. Geol.*, Vol. XX (1912), pp. 152–63; C. L. Dake, "The Problem of the St. Peter Sandstone," *Bull. Univ. Mo. School of Mines and Met.*, Vol. VI, No. 1 (1921); A. C. Trowbridge and M. E. Mortimore, "Correlation of Oil Sands by Sedimentary Analysis," *Econ. Geol.*, Vol. XX (1925), pp. 409–23; W. Hoppe, "Beiträge zur Geologie und Petrographie des Buntsandsteins im Odenwald. II. Petrographie. 2. Die Gemengteile des Buntsandsteins und die Gesteine der einzelnen Buntsandsteinstufen," *Notizbl. d. Ver. f. Erdkunde u. d. Geol. L.A. zu Darmstadt*, Folge V, Heft 10 (1927); G. B. Cressey, "The Indiana Sand Dunes and Shore Lines of the Lake Michigan Basin," *Geog. Soc. Chicago Bull. 8* (1928); William A. P. Graham, "A Textural and Petrographic Study of the Cambrian Sandstones of Minnesota," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 696–716; *Testing and Grading of Foundry Sands—Standards and Tentative Standards* (Chicago: Amer. Foundrymen's Association, 1931); Theresia Guggenmoos, *op. cit.*

[15] C. K. Wentworth, "A Laboratory and Field Study of Cobble Abrasion," *loc. cit.*; "The Shapes of Beach Pebbles," *U.S. Geol. Surv. Prof. Paper 131* (1921), pp. 75–83; "A Method of Measuring and Plotting the Shapes of Pebbles," *U.S. Geol. Surv. Bull.* 730 (1922), pp. 91–102; "A Field Study of the Shapes of River Pebbles," *loc. cit.*; "Pebble Wear on the Jarvis Island Beach," *Wash. Univ. Studies, Sci. and Tech.*, No. 5 (new ser., 1931), pp. 11–37; "The Shapes of Rock Particles: A Discussion," *Jour. Geol.*, Vol. XLI (1933), pp. 306–9.

Cox[16] likened roundness to sphericity and expressed it as the ratio of the area of grain cross section to the area of a circle whose perimeter is equal to that of the grain. His method has been modified by Tickell[17] and was used by MacCarthy[18] in making a study of beach and eolian sands. Lamar[19] devised a means of determining what he termed the "angularity" of sand grains by measuring the porosity of a particular size grade. Expressing roundness as a function of porosity, he thus obtained a mean roundness value for all grains of about the same size.

These "roundness" classifications, however, have been set up without full realization of the fundamental difference between shape and roundness. Roundness should only be used to express the quality developed by gentle attrition or, in some cases, by solution.[20] The investigators mentioned above assumed the end product of wear to be a spherical-shaped particle, unless modified by a greater ease of abrasion in certain directions. The effect of original shape was disregarded. Tester[21] recognized this defect of earlier classifications and attempted to devise a quantitative method for measuring the actual degree of wear. He determined roundness by outlining what he considered to be the approximate initial shape of the grain in order to determine the original lengths of the edges. His roundness value was then derived by a summation of the ratios between the portion of each edge worn away and the original length of that edge. There are theoretical objections to this method; moreover, workers will differ considerably in determining the positions and lengths of the so-called

[16] E. P. Cox, "A Method of Assigning Numerical and Percentage Values to the Degree of Roundness of Sand Grains," *Jour. Paleon.*, Vol. I (1927), pp. 179–83.

[17] F. G. Tickell, *The Examination of Fragmental Rocks* (Stanford University Press, 1931).

[18] G. R. MacCarthy, "The Rounding of Beach Sands," *loc. cit.;* "Eolian Sands: A Comparison," *loc. cit.*

[19] J. E. Lamar, "Geology and Economic Resources of the St. Peter Sandstone of Illinois," *Ill. Geol. Surv. Bull. 53* (1927), pp. 148–51.

[20] H. Wadell, "Volume, Shape, and Roundness of Rock Particles," *Jour. Geol.*, Vol. XL (1932), pp. 443–51; "Sphericity and Roundness of Rock Particles," *ibid.*, Vol. XLI (1933), pp. 310–31.

[21] A. C. Tester, "The Measurement of the Shapes of Rock Particles," *Jour. Sed. Petrol.*, Vol. I (1931), pp. 3–11.

"original" edges. Use of the method requires an expenditure of time that is scarcely justified by the results achieved.

Szadeczky-Kardoss[22] has also proposed a method of measuring degree of wear. It is based upon a determination of the percentages of flat, concave, and convex surfaces on a grain or pebble. The degree of wear of an individual particle, however, is not expressed by a single number but by the percentage of each type of surface. In practice Szadeczky-Kardoss recommends the classification of the grains by inspection into six classes (four of which are subdivided), based upon the relative amounts of the three types of surface. This method is objectionable because many grains which have not been worn to the slightest degree possess a fairly high percentage of convex surfaces, depending upon the character of the fractures and of the original shape. A zero value for degree of wear would be shown only by grains consisting entirely of concave surfaces.

A rapid method of classifying sand grains into groups on the basis of a qualitative estimation of the degree of wear has been used by Guggenmoos [23] in an attempt to relate roundness features to mode of origin. A similar method has been used by the writers.

The most detailed studies of the shape and degree of wear of sand grains are those of Wadell.[24] This investigator has developed quantitative expressions for these features, based upon their significance with respect to processes of sedimentation. He restricts the term "roundness" to an expression of the degree of wear suffered by the particle under conditions of gentle attrition (recognizing, however, that this property may also result from solution) and expresses shape

[22] E. v. Szadeczky-Kardoss, "Die Bestimmung des Abrollungsgrades," *Centralbl. für Min.* (1933), Abt. B, pp. 389–401.

[23] Theresia Guggenmoos, *op. cit.* Guggenmoos calls her divisions *Formengruppen* ("shape-groups"), but her descriptions indicate that she based them chiefly upon degree of wear.

[24] H. Wadell, "Volume, Shape, and Roundness of Rock Particles," *loc. cit.;* "Sphericity and Roundness of Rock Particles," *loc. cit.;* "Shape Determinations of Large Sedimental Rock-Fragments," *Pan. Amer. Geol.*, Vol. LXI (1934), pp. 187–220; "Some New Sedimentation Formulas," *Physics*, Vol. V (1934), pp. 281–91; "The Coefficient of Resistance as a Function of Reynolds Number for Solids of Various Shapes," *Jour. Franklin Inst.*, Vol. CCXVII (1934), pp. 459–90; "Volume, Shape, and Roundness of Quartz Particles," *loc. cit.*

in terms of "sphericity," or approach to spherical form. This usage has been adopted in the present paper.

Wadell defines roundness (P) as

$$P = \frac{\sum\left(\frac{r}{R}\right)}{N}$$

or

$$P = \frac{N}{\sum\left(\frac{R}{r}\right)},$$

where r is the radius of curvature of a plane corner (i.e., a corner as viewed in a plane area, projection area, or cross section, whose radius of curvature is equal to or less than the radius of the maximum inscribed circle in the given area), R is the radius of the maximum circle which can be inscribed within the area of the grain projection, and N is the number of corners in the given plane, the r of each being determined. The second formula sometimes gives slightly different roundness values and is preferable to the first for reasons outlined by Wadell.[25] Sphericity is defined as

$$\psi = \frac{s}{S},$$

where s is the surface area of a sphere of the same volume as the particle, S the actual surface area of the particle, and ψ the true sphericity. For measurements of the sphericity of sand grains, however, the following practical formula is used:

$$\phi = \frac{d_c}{D_c},$$

where d_c is the diameter of a circle equal in area to the area obtained in the grain reproduction of the "standard size"[26] when the grain rests on one of its larger faces, more or less parallel to the plane of the longest and intermediate diameters, D_c is the diameter of the smallest circle circumscribing the grain reproduction of the "standard size," and ϕ is the sphericity value obtained by this method. Wadell has shown that, for most geometrical shapes, the ϕ value closely

[25] "Volume, Shape, and Roundness of Quartz Particles," *loc. cit.*

[26] *Ibid.*

approaches the ψ value.[27] The chief deviation occurs in the case of very flat shapes.

THE SAMPLES STUDIED

The Mississippi River Commission, during 1932 and 1934, collected over six hundred samples from the bed of the river between Cairo, Illinois, and the Gulf of Mexico. Samples were also collected from the Atchafalaya River, the upper Mississippi, and the principal tributaries of the river. The sampler used consists of a "steel pipe 4 inches in inside diameter and 4 feet long, closed at one end, and flaring at the other end to a diameter of about 8 inches. The device is attached by means of a bail to a $1\frac{1}{4}$-inch rope, with which it is controlled from the boat."[28] After the sampler is filled by being towed downstream, it is "pulled in, the contents emptied by dropping the open end of the pipe on a board, and a sample of the material is placed in a properly marked can."[29] This method of sampling necessarily involves some mixing of sediments deposited at different periods, since the sampler digs several inches below the surface. In addition, probably some of the finest materials are lost when the sampler is emptied. These conditions are sources of error in mechanical analyses of the sediments but probably do not seriously affect the results of shape and roundness studies.

Mechanical analyses and absolute specific gravity determinations of the samples have been made by the Soil Mechanics Laboratory of the United States Waterways Experiment Station, and the results for all samples collected up to the end of May, 1934, have been published.[30] After analysis, the samples were split in half with a Jones sample splitter—one half being retained at the Experiment Station, the other sent to Louisiana State University for petrographic studies. Mineral analyses have been made of a selected series of these samples.[31]

[27] *Ibid.*

[28] *Studies of River Bed Materials and Their Movement, with Special Reference to the Lower Mississippi River* (U.S. Waterways Exper. Sta., Miss. River Comm., Paper 17 [1935], p. 120).

[29] *Ibid.*, p. 121. [30] *Ibid.*, pp. 116–61.

[31] R. Dana Russell, "Mineral Composition of Mississippi River Bed Materials" (awaiting publication). Samples from the principal tributaries of the river have also been analyzed for mineral composition, and the results are being prepared for publication.

Most of the samples consist chiefly of material of sand size, but several are gravels, and some consist largely of silt and clay. A progressive downstream decrease in mean grain size is evident from mechanical analyses of the samples,[32] but the decrease is far from uniform. A sample of fine sand may be succeeded by one of gravel, or vice versa.

For roundness and shape studies, samples were chosen at intervals of about 100 miles from Cairo to the Gulf, with additional samples above and below the mouths of important tributaries. Samples from the St. Francis, White, Arkansas, and Red rivers were also analyzed for comparison. All samples were collected from the thalweg. Data on the locations from which the samples were secured are given in Tables 1 and 2 and in Figure 1. The mechanical composition of the samples is presented in Table 3.

METHODS OF STUDY

At the beginning of the investigation all previously described methods were considered. Tester's method[33] appeared to be the only quantitative method directly applicable to the study of the roundness of sand grains as distinct from their shape. This method, however, is not only very time-consuming but is subject to the influence of personal judgment and to theoretical objections; hence the results which might be secured apparently would not justify the time required.

Any quantitative method for measuring the roundness of sand grains has the disadvantage that the time necessary to obtain results considerably limits the number of samples which may be analyzed. Qualitative methods, though they yield somewhat less accurate data, permit the study of more samples in a given time interval. In the present investigation it appeared more desirable to use a relatively rapid method of classifying grains by inspection than to attempt to devise a satisfactory quantitative procedure for measuring each grain. Accordingly, a method was used in which the grains were classified into groups based upon degree of wear. Twenty-one samples were analyzed in this way.

[32] *Studies of River Bed Materials and Their Movement, etc.*, pp. 123–43.

[33] Tester, *op. cit.*

During the course of this phase of the study Wadell described his method of quantitatively determining roundness and sphericity values for each grain.[34] Since his method appears to rest upon a

TABLE 1

MISSISSIPPI RIVER SAMPLES

Sample No.	Miles below Cairo, Ill.	Position in River	Date Sample Obtained	Approximate Depth of Water in Feet
M-7	7	Thalweg, straight reach	9–10–32	20
M-144	144	Thalweg, pool	9–13–32	42
M-146	146	Thalweg, crossing	9–13–32	23
M-293¾	293¾	Thalweg, head of crossing	9–16–32	25–29
M-300¾	300¾	Thalweg, head of crossing	9–16–32	33
M-385½	385½	Thalweg, crossing	6– 8–34	29
M-396	396	Thalweg, crossing	6– 7–34	23
M-403	403	Thalweg, crossing	6– 7–34	16
M-498¾	498¾	Thalweg, straight reach	8–22–32	41–44
M-600	600	Thalweg, head of pool(?)	8–25–32	20–30
M-760¼	760¼	Thalweg, crossing(?)	8–26–32	19–35
M-760½	760½	Thalweg, crossing	8–26–32	30–40
M-773½	773½	Thalweg, crossing	8–27–32	25–30
M-867½	867½	Thalweg, crossing(?)	8–28–32	45–55
M-968½	968½	Thalweg, crossing	4–30–34	80–94
M-972¼	972¼	Thalweg, pool(?)	4–30–34	95–105
M-1062¼	1,062¼	Thalweg, straight reach	5– 3–34	65–70

TABLE 2

TRIBUTARY SAMPLES

Sample No.	River	Miles above Mouth	Position in River	Date Sample Obtained	Depth of Water in Feet
75B	St. Francis	5.5	Thalweg, crossing	6– 9–34	8
88B	White	10.9	Thalweg, crossing	6– 8–34	14
46A	Arkansas	17.7	Thalweg, crossing	6– 8–34	7
36M	Red	36.0	Thalweg, crossing	11–10–32	8

sound theoretical foundation and eliminates the personal factor almost completely, it was also used in the analysis of three of the samples. Additional samples would have been analyzed by this method had time been available, but more than three months were required for the necessary measurements and computations on these three.

[34] Wadell, "Volume, Shape, and Roundness of Quartz Particles," *loc. cit.*

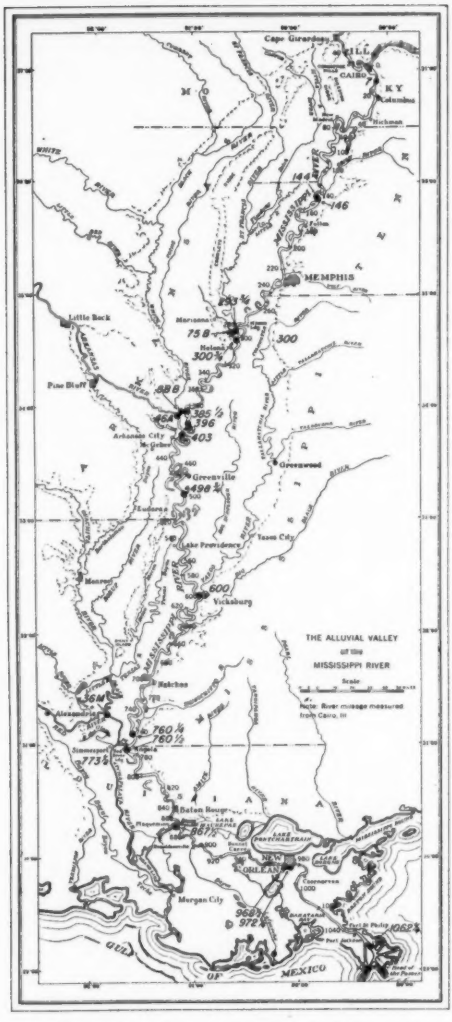

FIG. 1.—Map of the alluvial valley of the Mississippi River, showing the localities from which the samples studied were secured. Base map by courtesy of the Mississippi River Commission.

For both methods of analysis the samples were first separated into size grades. This was done by sieving, with standard Tyler wire-mesh sieves in which the diameter of the openings increased, from fine to coarse, approximately in the ratio of the square root of two.

TABLE 3

MECHANICAL ANALYSES

SAMPLE NO.	WEIGHT PERCENTAGE OF SAMPLE RETAINED ON EACH SIEVE*									
	14 M.	20 M.	28 M.	35 M.	48 M.	65 M.	100 M.	150 M.	200 M.	Pan
M-7	0.4	0.5	2.6	7.9	61.3	25.6	1.4	0.1	0.1	0.1
M-144	61.7	6.5	6.8	7.0	6.2	6.4	4.3	0.8	0.2	0.1
M-146	3.0	6.5	29.4	42.3	13.6	3.1	1.3	0.7	0.1	0.1
M-293¾	29.0	7.1	21.3	28.0	10.8	3.1	0.5	0.1	tr.	tr.
M-300¾	9.1	7.7	23.6	38.4	18.6	2.3	0.2	tr.	tr.	tr.
M-385½	0.1	0.1	0.5	10.2	63.3	22.4	2.8	0.4	0.1	0.1
M-396	.....	tr.	0.1	1.7	18.3	64.5	14.2	1.0	tr.	tr.
M-403	3.5	2.7	9.0	27.0	19.8	31.5	5.8	0.5	0.1	0.1
M-498¾	0.6	0.4	1.8	6.2	12.6	46.1	16.6	12.1	3.3	0.4
M-600	0.8	1.1	7.2	34.1	43.6	11.9	1.1	0.1	0.1	0.1
M-760¼	tr.	tr.	tr.	tr.	0.5	33.1	57.8	7.7	0.7	0.1
M-760½	0.5	0.4	3.4	34.0	43.2	17.0	1.3	0.1	0.1	tr.
M-773½	0.2	0.1	0.6	3.5	6.4	6.7	29.4	39.6	12.4	1.1
M-867½	0.1	tr.	tr.	tr.	1.2	41.7	48.6	7.1	0.7	0.4
M-968½	.....	.....	.....	tr.	tr.	4.9	74.0	18.5	2.0	0.5
M-972¼	.....	.....	tr.	1.6	66.1	24.6	5.4	2.2	tr.	tr.
M-1062¼	.....	.....	0.1	0.1	2.3	14.5	57.1	23.5	1.9	0.5
75B	43.7	1.1	4.9	16.0	13.9	4.0	2.4	1.5	0.8	11.7
88B	0.4	0.9	3.6	25.4	47.5	14.5	5.5	1.1	0.1	0.9
46A	.....	.....	.....	0.4	9.8	53.3	26.3	8.7	1.2	0.3
36M	.....	tr.	tr.	tr.	tr.	0.1	2.0	46.1	24.7	27.0

* For diameters of the sieve openings see n. 35. Sieves coarser than the 14-mesh were employed in the actual analyses, but for the purposes of this table all material coarser than the 14-mesh sieve has been combined.

Each sample was placed in the top member of a nested series of these sieves and shaken for 15 minutes in a Ro-Tap shaker. Six of the grades thus separated—the 35-, 48-, 65-, 100-, 150-, and 200-mesh grades—were used for the roundness studies. Grades coarser than the 35-mesh were not studied because most of the samples below mile 600 contained very little or no material coarser than this grade. Grains passing the 200-mesh sieve were also excluded from the investigation, except in the case of three pairs of samples chosen for

comparison studies by the visual-classification method, because observation showed this material to be almost wholly angular.[35]

For roundness determinations by the visual-classification method, each of the six grades of each sample was treated as follows: A fraction of the grade to be studied was split out by the use of a "microsplit,"[36] and the grains were spread out in a line across a lead tray. They were then examined under a binocular microscope, and each grain was classified on the basis of degree of wear as well-rounded, rounded, subrounded, subangular, or angular. A count was made of the number of grains of each type, several hundred grains being counted (average, 564) for each grade. Only quartz and feldspar grains were considered. The grouping into classes was based partly on comparison with photographs of type grains (Fig. 2) but chiefly by estimation, using the following criteria:

Angular.—Showing very little or no evidence of wear; edges and corners are sharp.

Subangular.—Showing definite effects of wear. The grains still have their original form, and the faces are practically untouched, but the edges and corners have been rounded off to some extent though the angles between faces may still be sharp.

Subrounded.—Showing considerable wear. The edges and corners are rounded off to smooth curves, and the area of the original faces is

[35] The designations used for the grades, and their sizes, are as follows:

Designation of Grade (Mesh)	Sieve Sizes (Diameter of Openings in Mm.)	
	Passed by	Retained on
14	10-mesh, 1.651	14-mesh, 1.168
20	14-mesh, 1.168	20-mesh, 0.833
28	20-mesh, 0.833	28-mesh, 0.589
35	28-mesh, 0.589	35-mesh, 0.417
48	35-mesh, 0.417	48-mesh, 0.295
65	48-mesh, 0.295	65-mesh, 0.208
100	65-mesh, 0.208	100-mesh, 0.147
150	100-mesh, 0.147	150-mesh, 0.104
200	150-mesh, 0.104	200-mesh, 0.074
<200	200-mesh, 0.074	Pan

[36] A small sample splitter designed by G. H. Otto and described in "Comparative Tests of Several Methods of Sampling Heavy Mineral Concentrates," *Jour. Sed. Petrol.*, Vol. III (1933), pp. 30–39.

considerably reduced, but the original shape of the grain is still distinct.

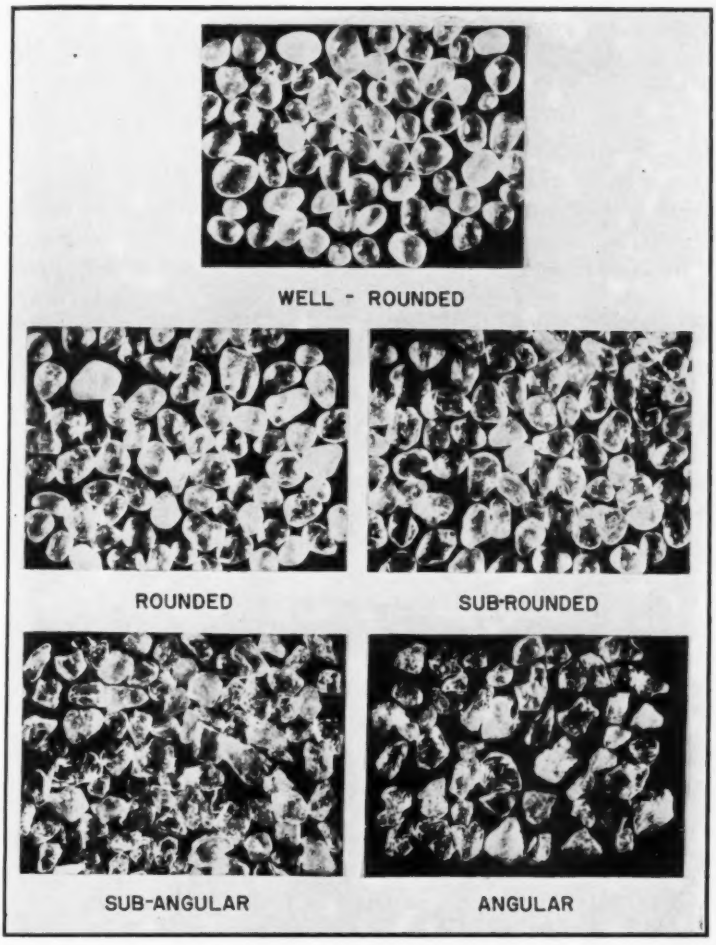

FIG. 2.—Photomicrographs of sand grains showing various degrees of rounding (× 8.5).

Rounded.—Original faces almost completely destroyed, but some comparatively flat surfaces may be present. There may be broad

re-entrant angles between remnant faces. All original edges and corners have been smoothed off to rather broad curves.

Well-rounded.—No original faces, edges, or corners left. The entire surface consists of broad curves; flat areas are absent. The original shape of the grain may be suggested by its present form, however.

In classifying grains on the basis of these criteria attention was focused on the amount of wear suffered by the grain as shown by the character of the edges and corners. The "shape" of the grain was not considered. There is, however, a subconscious tendency to assign grains whose shape approaches the spherical to a higher roundness class than is warranted by the degree of wear which they have suffered. This tendency was kept in mind during the analyses in an attempt to minimize its influence, apparently with a fair degree of success (see pp. 247–49).

Many of the grains show freshly broken surfaces. These, without exception, were placed in the angular group, regardless of the degree of rounding shown by the rest of the grain. Similarly, grains which had been fairly well rounded, then fractured, and somewhat rounded subsequent to the fracturing were classified on the basis of the degree of wear shown by the edges bordering the fracture, i.e., on the basis of the most recent effect. The reasons for this procedure are: (1) the degree of rounding which a grain has suffered prior to fracturing is not always evident; (2) the writers were not primarily concerned with determining the specific property of roundness *per se* but rather with a determination of the extent to which the grains had been modified during transportation by the river as a result of the combined influence of various mechanical processes—grinding, fracturing, chipping, blasting by smaller grains, etc.—and, possibly, of the chemical process of solution; and (3) consistent assignment of all freshly fractured grains to the angular class was expected to yield information concerning the amount of chipping and fracturing suffered by the grains in the course of their transportation downstream.

The procedure used in analyzing the samples by the Wadell method was as outlined by Wadell,[37] with one modification. Instead

[37] "Volume, Shape, and Roundness of Quartz Particles," *loc. cit.*

of making camera lucida drawings of the grains, they were projected on a fine-textured ground-glass plate and the measurements made directly. In order to facilitate enlargement of the image to the "standard size,"[38] a table was constructed with a sliding shelf which could be placed at various elevations so that the distance between the ocular of the microscope and the ground-glass plate could be easily adjusted. The microscope was placed on the shelf and directly below the ground-glass plate, which was set flush with the table top. This procedure considerably reduces the time involved in securing data.

Fifty grains were measured from each size grade of each of the three samples, with the exception of the 150-mesh grade of the sample from mile 1,062¼, in which the results are based on 49 grains only. As in the analyses by the visual-classification method, only feldspar and quartz grains were considered.

RESULTS OF THE STUDIES

PRESENTATION OF DATA

The data secured by the visual-classification method of analysis are summarized in Table 4. The roundness numbers given were computed by multiplying the frequency percentage of grains in each roundness group by an arbitrarily assigned number as follows: angular, 1; subangular, 2; subrounded, 3; rounded, 4; well-rounded, 5. The products were then totaled and divided by 100. An example is given below:

SAMPLE M-7, 35-MESH GRADE

	Percentage	
Well-rounded.....	1.4×5=	7.0
Rounded.....	5.2×4=	20.8
Subrounded.....	30.8×3=	92.4
Subangular.....	45.4×2=	90.8
Angular.....	17.2×1=	17.2
		228.2

$$\frac{228.2}{100} = 2.28 = \text{roundness number}$$

The roundness number is thus an approximation of the mean degree of rounding of the sample; in the example the roundness number of 2.28 indicates that the sample, in average degree of rounding, is a

[38] *Ibid.*

little more than one-fourth of the way between the center of the subangular group and the center of the subrounded group.

TABLE 4

ROUNDNESS OF SAND GRAINS BY THE VISUAL-CLASSIFICATION METHOD

Sample No.	Size Grades Expressed in Mesh Numbers							
	35	48	65	100	150	200	<200	Weighted Mean
	Mississippi River Samples							
M-7	2.28	2.35	2.29	2.15	1.40	1.12	*	2.33
M-144	2.25	2.49	2.24	1.97	1.21	1.28	1.13	2.20
M-146	2.36	2.45	2.24	2.06	1.43	1.28	1.11	2.35
M-293¾	2.45	2.33	2.00	1.48	1.41	1.12	*	2.37
M-300¾	2.33	2.34	2.09	1.60	1.54	1.16	*	2.27
M-385½	2.13	2.27	2.06	1.92	1.48	1.30	*	1.99
M-396	2.15	2.17	1.90	1.74	1.56	1.29	*	1.94
M-403	2.46	2.30	1.93	1.92	1.39	1.46	*	2.17
M-498¾	2.16	2.04	1.95	1.91	1.47	1.36	*	1.90
M-600	2.12	2.07	2.06	2.06	1.41	1.31	*	2.11
M-760¼	2.33	2.12	1.90	2.06	1.54	1.33	1.09	2.17
M-760½	2.36	2.22	2.06	2.03	1.47	1.24	1.10	2.21
M-773½	2.18	2.26	1.90	1.58	1.45	1.37	*	1.58
M-867½	1.96	1.70	1.66	1.61	1.53	1.39	*	1.63
M-968½	†	1.93	1.59	1.83	1.45	1.33	1.09	1.73
M-972¼	2.05	2.09	2.00	2.01	1.44	1.32	1.09	2.04
M-1062¼	1.97	2.05	1.65	1.49	1.46	1.29	*	1.50
	Tributary Samples							
75B (St. Francis)	2.30	2.10	1.91	1.61	1.29	1.10	*	2.11
88B (White)	2.10	2.06	2.01	1.81	1.50	1.33	*	2.04
46A (Arkansas)	2.13	2.01	1.98	1.71	1.47	1.27	*	1.87
36M (Red)	2.22	2.09	1.94	1.86	1.43	1.31	*	1.40
	Arithmetic Means (All Samples)							
	2.21	2.16	1.97	1.83	1.44	1.28	1.10	.....

* Not analyzed. † Not enough material for analysis.

The last column of Table 4 presents the weighted means of all six size grades. These figures were computed by recalculating the mechanical analysis of the sample to 100 per cent for the six grades

studied. The roundness number of each size grade was then multiplied by the percentage of material in that grade, and the products totaled and divided by 100, as follows:

SAMPLE M-7

Size Grade (Mesh)	Roundness Number	Percentage of Material in Grade		
35	2.28	× 8.2	=	18.70
48	2.35	× 63.6	=	149.46
65	2.29	× 26.6	=	60.91
100	2.15	× 1.5	=	3.23
150	1.40	× 0.1	=	0.14
200	1.12	× 0.1	=	0.11
			$\frac{232.55}{100}$	= 2.33

The results of the analyses by the Wadell method are presented in Table 5. For each size grade the maximum and minimum P (roundness) and ϕ (sphericity) value for the fifty investigated grains is given, as well as the arithmetic means of the values. Under the heading "Whole Sample," the arithmetic means of the values for all six grades are given, as well as weighted means. The latter were computed by multiplying the mean P and ϕ value of each size grade by the number of grains out of one million present in that grade,[39] totaling the products, and dividing the result by one million. This method differs from that used to determine the weighted means from the visual-classification method, in which the weight percentage of material in each size grade rather than the number of grains was used. The use of weight percentages emphasizes the effect of the coarser grades, which appears more desirable for roundness studies. Wadell,[40] however, recommends computations based on frequency; hence this system was used for the data secured by his method in order to insure uniformity with his results. Figures 3 and 4 present the distribution of the P and ϕ values of each sample divided into three volume classes and represented by means of histograms, as recommended by Wadell.[41] Four volume classes were determined,

[39] Computed as outlined by Wadell in *ibid.*

[40] *Ibid.* [41] *Ibid.*

but the 1.0–0.1 cu. mm. class contained so few grains that it was combined with the class 0.1–0.01 cu. mm.

Accuracy of the data.—As has been stated, the chief source of error in analyses by such a system as the visual-classification method lies in the factor of personal judgment. The criteria on which the classifi-

TABLE 5

DATA FROM ANALYSES BY THE WADELL METHOD

Mile No. of Sample	Size Grade (Mesh)	Maximum P Value	Minimum P Value	Arithmetic Mean of P Values	Maximum ϕ Value	Minimum ϕ Value	Arithmetic Mean of ϕ Values	Weighted Mean of P Values*	Weighted Mean of ϕ Values*
7	35	0.678	0.043	0.302	0.960	0.738	0.872	.....	.....
	48	.833	.072	.306	.945	.701	.852	.....	.....
	65	.910	.042	.304	.931	.705	.828	.....	.....
	100	.858	.058	.330	.935	.665	.800	.....	.....
	150	.541	.019	.097	.954	.660	.797	.....	.....
	200	0.353	0.023	.067	0.899	0.660	.799	.....	.....
Whole sample	.....	.....	.....	0.234	.....	.....	0.825	0.298	0.840
498¾	35	0.848	0.085	0.315	0.963	0.698	0.825	.....	.....
	48	.644	.092	.310	.937	.667	.831	.....	.....
	65	.890	.053	.279	.953	.642	.839	.....	.....
	100	.735	.033	.206	.946	.691	.815	.....	.....
	150	.625	.023	.143	.988	.636	.803	.....	.....
	200	0.482	0.022	.101	0.910	0.625	.785	.....	.....
Whole sample	.....	.....	.....	0.226	.....	.....	0.816	0.176	0.809
1,062¼	35	0.890	0.074	0.309	0.962	0.749	0.845	.....	.....
	48	.579	.060	.239	.978	.668	.824	.....	.....
	65	.536	.059	.199	.906	.675	.812	.....	.....
	100	.906	.026	.122	.963	.566	.788	.....	.....
	150	.390	.023	.118	.934	.673	.795	.....	.....
	200	0.323	0.024	.087	0.895	0.667	.787	.....	.....
Whole sample	.....	.....	.....	0.179	.....	.....	0.809	0.121	0.792

* Based on the size-frequency distribution of the grains (see text).

cation is based may be differently interpreted by various workers. Moreover, the same individual might place the division point between classes somewhat differently at one time than at another. Several tests were made, therefore, to determine the magnitude of this source of error.

To determine the variation in interpretation between different individuals, several samples were counted by Russell and Taylor independently. The results were almost identical. To further elimi-

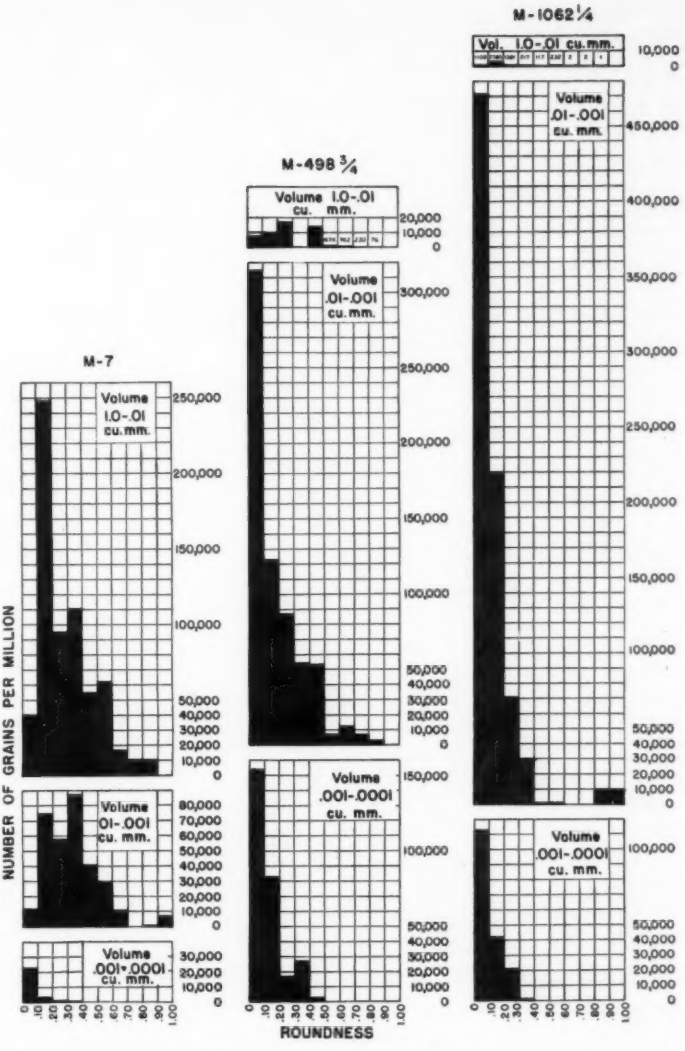

FIG. 3.—Distribution of one million grains of each sample classified according to volume and roundness (*P* value).

nate this source of error, however, Taylor made all the determinations on which the data presented are based.

To determine the extent of variations in interpretation with time, several samples were counted, laid aside for more than a week, and

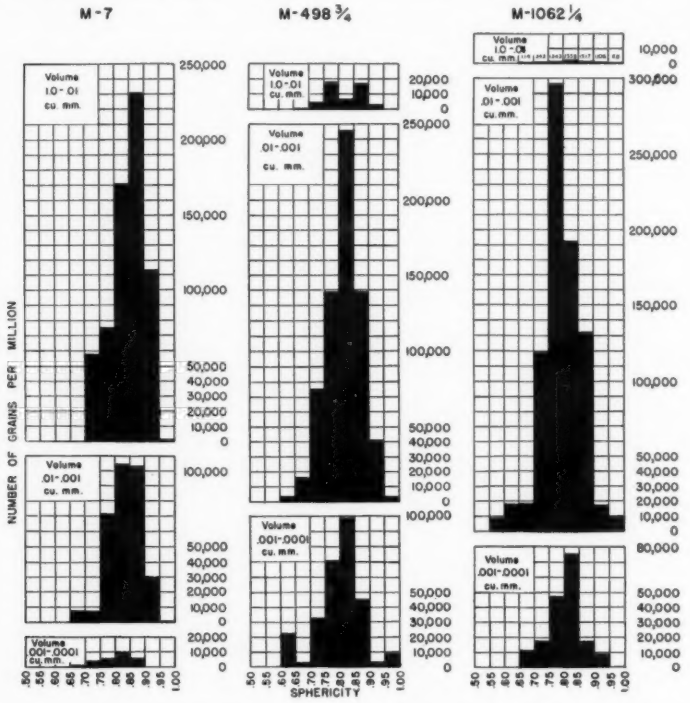

FIG. 4.—Distribution of one million grains of each sample classified according to volume and sphericity (ϕ value).

recounted without reference to the results secured from previous counts. Again the error was negligible. As a further check, several "cuts" were made from the same grade of a particular sample, and each "cut" counted individually at different times. This test showed that the variation in percentage of material in each roundness class was somewhat greater than the sampling error in some cases, but the roundness numbers agreed closely. Of the seven grades on which two

or more check analyses were run, five showed a variation of less than 0.06 between the maximum and the minimum roundness numbers determined by the various counts. Two showed variations slightly greater than 0.10, but fewer grains were counted in these two cases. These tests apparently indicate that the criteria used to separate the grains into roundness classes were applied with a fairly high degree of uniformity.

Another source of error lies in the possible effect of shape upon the grouping of the grains into roundness classes. As has been stated, there is a tendency for grains possessing a fairly high degree of sphericity to be placed in a higher roundness class than warranted by the degree of wear which they have suffered. To eliminate this effect as much as possible, attention was focused upon the degree of wear shown by the corners and edges, regardless of the shape of the grain, and grains approaching the spherical in shape were subjected to a special scrutiny. In spite of this precaution, it seemed possible that this source of error had not been completely eliminated. As a check upon this point, and to determine the relation between the roundness classes and the Wadell values, the latter were determined for the type roundness slides (Fig. 2) and for material picked by the visual method from the 35-mesh grade of sample M-7. The results are shown in Table 6. The mean ϕ values for the type slides and for the grains picked from sample M-7 agree rather closely, but the mean P values for the type slides are higher than those for the sample M-7 material, with the exception of the well-rounded class. Since only seven grains belonging in this class could be found in the several hundred examined, this value probably is not very reliable. The generally lower mean P values for the material from sample M-7 suggest that the division points between classes were placed somewhat lower in working with the Mississippi River sands than in picking grains for the type slides.

Table 6 also shows that the mean ϕ values are higher for the higher roundness classes. This relationship suggests that the effect of grain shape upon the classification into roundness groups was not eliminated and that grains of high sphericity were placed in a higher roundness group than justified by their degree of wear. On the other hand, one would naturally expect a relationship to exist between

roundness and sphericity. Grains which have suffered a considerable amount of wear should, on the average, possess higher sphericity values than unworn grains of the same mineral. To determine the

TABLE 6*

WADELL VALUES FOR MATERIAL PICKED BY THE VISUAL-CLASSIFICATION METHOD

Designation by Visual Method	Number of Grains Measured		Mean P Values			Mean ϕ Values		
	1	2	1	2	3	1	2	3
Well-rounded	50	7	0.756	0.804	0.780	0.92	0.90	0.91
Rounded	40	25	.646	.580	.613	.89	.89	.89
Subrounded	50	25	.446	.370	.408	.87	.87	.87
Subangular	50	25	.246	.177	.211	.83	.83	.83
Angular	40	25	0.142	0.104	0.123	0.79	0.84	0.815

* Columns labeled 1 give data for the type roundness slides. Columns labeled 2 give data for material picked from the 35-mesh grade of sample M-7. Columns labeled 3 give the arithmetic means of cols. 1 and 2.

extent of this relationship, the data for all the grains measured from the 35-mesh grade of each sample were plotted, using the ϕ value as ordinate and the P value as abscissa (Fig. 5). The one hundred fifty points are quite scattered, but their distribution suggests a relationship. To bring this out the P values were divided into groups corresponding approximately with the grouping used in the visual-classification method, as follows:

	P Values
Angular	0.00 — 0.15
Subangular	0.15 — 0.30
Subrounded	0.30 — 0.50
Rounded	0.50 — 0.70
Well-rounded	0.70 — 1.00

Using the mean P value of all grains falling within each group as abscissa, and the mean ϕ value of the same grains as ordinate, the solid-line curve of Figure 5 was plotted. This curve shows a definite rise in ϕ value with increasing P value up to a P value of about 0.40, where the curve flattens. For comparison, the mean P and ϕ values of Table 6 (cols. 3) were similarly plotted, using a broken line. The left half of this curve lies somewhat lower than the first curve but parallels it fairly closely up to a P value of 0.40, where the first curve

flattens and the second continues to rise, crossing the first between P values of 0.45 and 0.50. The relationship between these curves suggests that the shape of the grains did not appreciably affect their classification in the lower roundness groups but did have an effect in the higher classes. Since the effect is slight, however, and the percentage of rounded and well-rounded grains is quite low in the samples studied, the error produced in the results seems to be negligible. Errors in the visual-classification method due to the element of personal judgment thus appear to be too small to seriously affect the results.

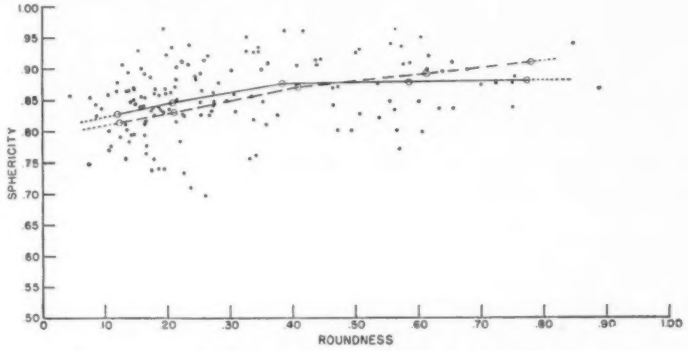

FIG. 5.—Relationship between roundness (P) and sphericity (ϕ)

The elements of error involved in determinations by the Wadell method have been discussed by Wadell.[42] The ϕ values tend to be too high in the case of flat grains; hence, since much of the quartz in the samples is "platy,"[43] and some of the feldspar also occurs as flat grains, the ϕ values in some cases probably are greater than the true sphericity (ψ) values. The chief source of error, however, lies in the sampling, as only fifty grains from each size grade were measured. Moreover, only three samples could be analyzed in the time available. Although these are from similar points in the river (the thalweg of a straight reach), there is a possibility that they are not representative; hence the data scarcely justify positive conclusions.

[42] *Ibid.*

[43] R. Dana Russell, "Frequency Percentage Determinations of Detrital Quartz and Feldspar," *Jour. Sed. Petrol.*, Vol. V (1935), pp. 109–14.

VARIATIONS IN ROUNDNESS AND SPHERICITY

Relationship between size of grain and roundness and sphericity.—A number of observers have noted that a relationship exists between "roundness" and grain size (see n. 10). In some cases shape, rather than roundness, was the quality investigated; hence there appears to be a tendency for the larger grains to possess both higher sphericity values and a higher degree of roundness. This relationship is also shown by the Mississippi River samples. Figure 6 shows the mean roundness numbers of all twenty-one samples plotted against grain size expressed in mesh numbers, and the mean P and ϕ values of the three samples analyzed by the Wadell method similarly plotted. In both cases roundness decreases rapidly with decreasing size of grain, and a similar relationship is shown between the sphericity values and the grain size. This relationship, however, is not uniformly applicable to individual samples. In eight of the twenty-one samples the 48-mesh grade shows the best rounding, and in two the 100-mesh grade is better rounded than either the 65- or 150-mesh (see Table 4). The Wadell values exhibit similar discrepancies. In sample M-7 the 100-mesh grade shows by far the highest mean P value, and the 48- and 65-mesh grades possess slightly higher values than the 35-mesh (Table 5). In view of the fact, however, that the 100-mesh grade of this sample showed a lower degree of rounding than any of the three coarser grades in the analysis by the visual method, this high mean P value may well be the result of a sampling error. The relationship between ϕ values and grain size is also variable. In sample M-498$\frac{3}{4}$ the 65-mesh grade possesses the highest mean sphericity, and in sample M-1062$\frac{1}{4}$ the 150-mesh grade shows a higher mean ϕ value than either the 100- or 200-mesh grades.

MacCarthy[44] has noted a relationship between "roundness" and the prevalence of a particular grain size in beach and "beach dune" sands, the commonest size showing the best "rounding." MacCarthy employed Cox's method[45] in his analyses. This method involves the measurement of the degree of circularity of a cross section of the grain, and hence is a measurement of shape rather than of roundness. Wadell's ϕ value corresponds closely to Cox's

[44] "The Rounding of Beach Sands," *loc. cit.*; "Eolian Sands: A Comparison," *loc. cit.*

[45] Cox, *op. cit.*

"roundness" value, but there appears to be very little relationship between the mean ϕ values and the amount of material in the various size grades. Although in sample M-498¾ the 65-mesh grade contains

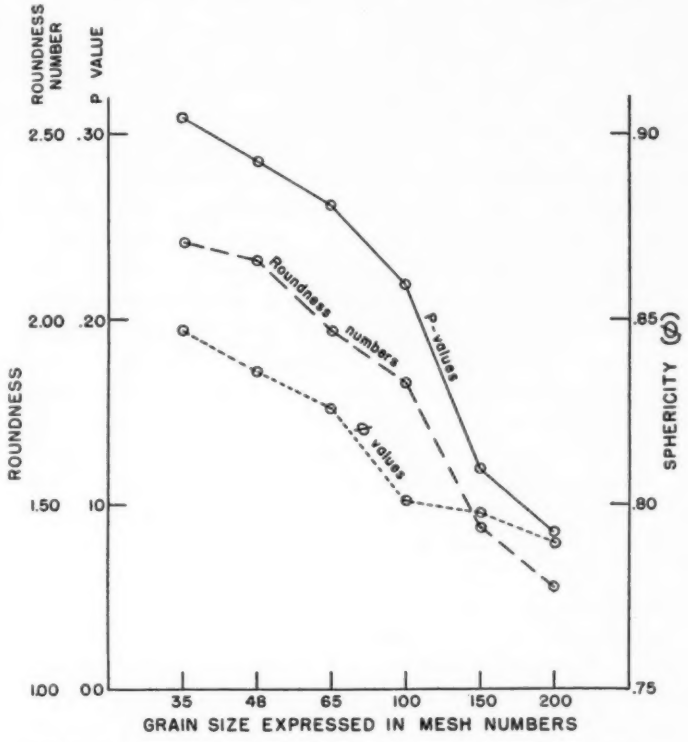

FIG. 6.—Relationship between grain size and roundness and sphericity

the most material and also possesses the highest mean ϕ value, in sample M-1062¼ the 100-mesh grade shows a lower mean sphericity than the grades on either side, though it contains 57 per cent of the material. The P values do not show the slightest relationship to prevalence of size grade, but data on three samples scarcely justify generalizations on this point. If any relationship between roundness and prevalence exists, however, it should be shown by the data from

the visual method. No such relationship is apparent from inspection of Tables 3 and 4, but it may be hidden by variations in the data of individual samples. To minimize such variations, the mechanical analyses of the samples were recalculated to 100 per cent for the six grades studied, and the samples then grouped on the basis of the grade containing the maximum amount of material according to the recalculated analyses. Five samples showed the maximum in the 35-mesh grade, six in the 48-, four in the 65-, four in the 100-, and two in the 150-mesh. For each group the amount of material in each size grade and the roundness number of each grade were averaged. The results are given in Table 7. The relationship between roundness and size is again evident, but no marked correlation between roundness and prevalence is shown.

Relationship between mineral composition and roundness.—Comparative roundness studies should, if possible, be limited to grains of one mineral. This is readily accomplished when the "light" portion of the sediment consists almost wholly of quartz. In the Mississippi River samples, however, feldspars make up between 20 and 25 per cent of the average sample. The predominant types are oligoclase and andesine, whose specific gravities are so close to that of quartz as to make gravity separations impossible. Other minerals present in the "light" separates can be distinguished from quartz on sight, but, unfortunately, this is not true of many of the feldspar grains.[46] Separation of the quartz from the feldspar therefore requires either a determination of the optical character of doubtful grains, by means of an interference figure, or a staining procedure. In the Mississippi River samples the grains whose identity is not definitely determinable on sight make up more than 25 per cent of the average sample, so that the time involved in securing interference figures becomes an important factor. Moreover, a petrographic microscope must be used, while the visual classification of the grains into roundness groups is accomplished more readily and more accurately by the use of a binocular microscope. Staining procedures involve the use of hydrofluoric acid, which attacks quartz and hence destroys the original features of the grains. For these reasons the feldspars were

[46] Russell, "Frequency Percentage Determinations of Detrital Quartz and Feldspar," *loc. cit.*

included with the quartz in the determinations, although other minerals were excluded.

Mineral analyses have been made of all the samples analyzed for roundness.[47] The mineral composition of the "light" separate of the

TABLE 7

ROUNDNESS AND PREVALENCE

Groups*	Size Grades Expressed in Mesh Numbers					
	35	48	65	100	150	200
	Mean Percentage of Material in Each Size Grade, According to Recalculated Mechanical Analyses					
I	52.4	29.5	10.4	5.2	1.7	0.8
II	20.0	56.2	20.0	3.0	0.7	0.1
III	10.1	16.2	50.7	16.1	5.7	1.2
IV	0.1	1.1	23.6	59.5	14.3	1.4
V	1.9	3.3	3.5	16.4	51.6	23.3
All samples	20.3	26.7	22.7	18.0	9.3	2.9
	Mean Roundness Numbers					
I	2.34	2.34	2.10	1.74	1.38	1.18
II	2.17	2.18	2.08	2.00	1.45	1.27
III	2.22	2.13	1.94	1.82	1.47	1.34
IV	2.09	1.95	1.70	1.75	1.49	1.33
V	2.20	2.17	1.92	1.72	1.44	1.34
All samples	2.21	2.16	1.97	1.83	1.44	1.28

* The groups are based on the location of the maximum amount of material according to the recalculated mechanical analyses (see text). In Group I (five samples) the maximum occurs in the 35-mesh grade; in Group II (six samples) in the 48-mesh; in Group III (four samples) in the 65-mesh; in Group IV (four samples) in the 100-mesh; and in Group V (two samples) in the 150-mesh.

100-mesh grade has been determined for each sample, and additional grades have been analyzed in the case of some samples;[48] hence it is possible to determine the relationship between the amount of feldspar present and the mean roundness. In Figure 7 the roundness

[47] The mineral composition of most of the samples is given in "Mineral Composition of Mississippi River Bed Materials" (awaiting publication). Data on the others will appear later.

[48] R. Dana Russell, "The Size Distribution of Minerals in Mississippi River Sands," *Jour. Sed. Petrol.*, Vol. VI (1936), pp. 125–42.

number of the 100-mesh grade of each sample is plotted against the relative amounts of quartz and feldspar, expressed as the quartz to quartz plus total feldspar ratio. This ratio represents the number of quartz grains in 100 grains of quartz and feldspar together.

Figure 7 shows a correlation between roundness and mineral composition—higher quartz content being usually accompanied by a lower degree of roundness. The points fall in a rather small area

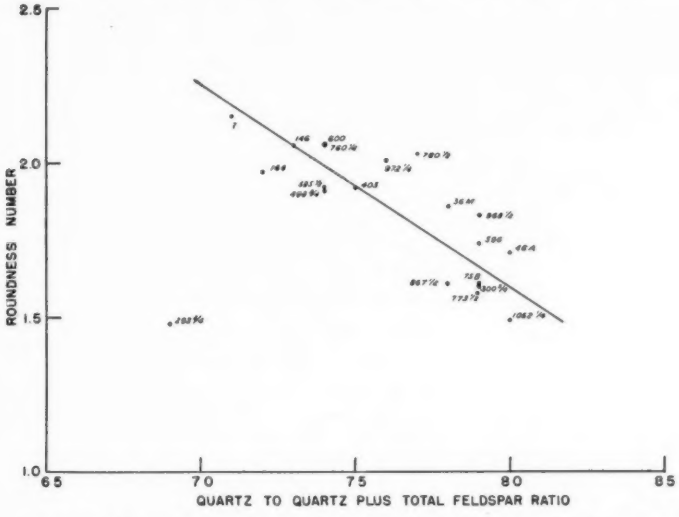

FIG. 7.—Relationship between roundness and the relative amounts of quartz and feldspar.

with two exceptions—sample M-293¾ from the Mississippi and sample 88B from the White River. The latter was omitted from the graph because its values (quartz to quartz + total feldspar ratio = 58, roundness number = 1.81) place it so far to the left that the graph would have to be widened considerably to include it. Neglecting these two samples, the relationship can be expressed approximately by the straight line of Figure 7.

The Wadell *P* values suggest a similar correlation with the relative amount of quartz and feldspar. The ϕ values do not, the 100-mesh grade of sample M-498¾ possessing both a higher mean ϕ value and a

higher quartz content than the same grade of sample M-7. Three samples, however, are not enough to establish or disprove a possible correlation.

Progressive downstream changes in roundness and sphericity.—In Figure 8 the roundness numbers of the various grades of each of the Mississippi River samples are plotted against the sample numbers, which represent the mileage below Cairo, Illinois. The data for the tributary samples are shown as points, plotted according to the position of the mouth of the tributary. In some cases the distance between Mississippi River samples above and below the mouth of a tributary has been exaggerated to allow space for plotting the data from the tributary sample. The values for the three pairs of samples (M-144–M-146; M-760$\frac{1}{4}$–M-760$\frac{1}{2}$; and M-968$\frac{1}{2}$–M-972$\frac{1}{4}$) were averaged in plotting the graph.

Although the roundness values shown in Figure 8 fluctuate considerably, some slight progressive changes are evident. There is a general division of the roundness numbers into two groups, the values for the three coarsest size grades (35-, 48-, and 65-mesh) being separated from those of the two finest grades studied (150- and 200-mesh) by a considerable gap. The line representing the roundness numbers of the 100-mesh grade fluctuates back and forth within this zone, sometimes approaching closer to one group, sometimes to the other. The two finest grades remain fairly constant, showing no marked progressive change in degree of rounding, though there is a suggestion of a very slight increase. The three coarsest grades, on the other hand, show a decrease in roundness downstream. The weighted mean roundness numbers of the samples also decrease slightly downstream, as is to be expected from the downstream increase in percentage of the finer, more angular, grains.

Figure 8 also suggests that the character of the bed load contributed to the Mississippi by the four tributaries from which samples were studied has little effect upon the character of the Mississippi River bed load and bed material. In many cases the change in roundness numbers, of the same size grades, from the Mississippi sample above the mouth of a tributary to the one below is in the opposite direction from what would be expected from the roundness values of the tributary sample. This fact implies that the

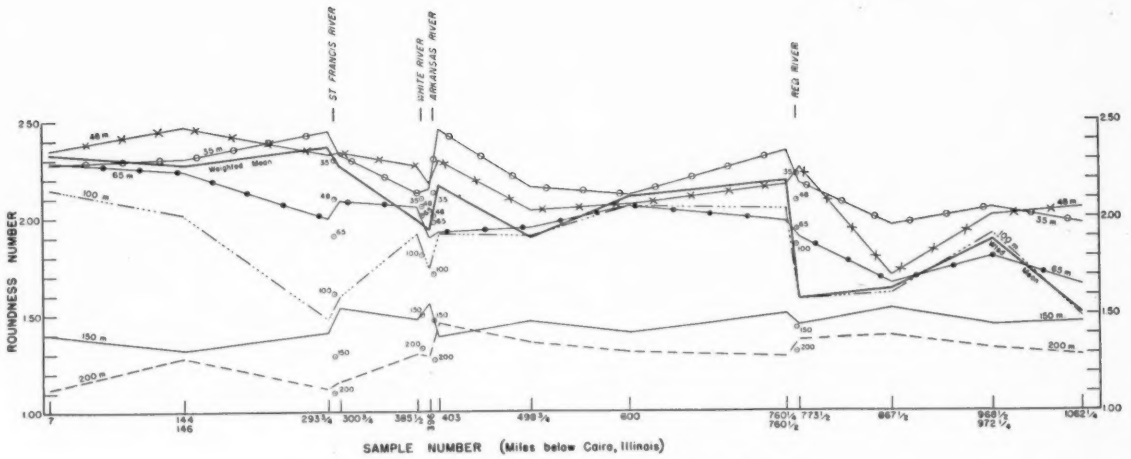

FIG. 8.—Relationship between roundness and distance downstream

amount of bed load contributed by these tributaries is too small to appreciably affect the character of the Mississippi River bed load and bed material. Since only one sample was analyzed from each tributary, however, this conclusion is no more than tentative.

The Wadell roundness values show a similar downstream decrease. Figure 3 indicates that, for the three samples studied, the coarsest and finest sizes (volume classes 1.0–0.01 and 0.001–0.0001 cu. mm.) remain fairly constant, but the intermediate sizes (volume class 0.01–0.001 cu. mm.) obviously decrease in roundness downstream. The mean roundness values for the individual size grades are plotted in Figure 9*B*, with the roundness numbers (determined by the visual method) of the same samples shown directly above in Figure 9*A* for comparison. Figure 9*B* shows that, in a downstream direction, the roundness values for the 35-, 150-, and 200-mesh grades remain fairly constant; the values for the 48-mesh rise slightly and then decrease; and the values for the 65- and 100-mesh grades decrease decidedly. The arithmetic and weighted means of each sample (see Table 5) also decrease downstream, the latter much more markedly, owing to the fact that the three samples show a progressive downstream increase in the percentage of fine material (Table 3).

Considering the differences between the two methods employed in the analyses, Figures 9*A* and 9*B* show a remarkable similarity, especially in the mean values for the samples. This similarity argues well for the accuracy of the visual method—implying that a method of this type, if carefully used, will yield data almost as reliable as those furnished by procedures involving the measurement of individual grains and requiring much more time.

Figures 4 and 10 present data on downstream changes in the mean ϕ values of the samples. Figure 4 shows that the sphericity of the coarsest and finest particles (volume classes 1.0–0.01 and 0.001–0.0001 cu. mm.) remains fairly constant, though the values for the coarsest volume class show a suggestion of a slight decrease. In the middle volume class (0.01–0.001 cu. mm.) a downstream decrease in sphericity is clearly evident. The individual size grades (Fig. 10) show considerable fluctuations in mean ϕ values, but the values for the coarser grades and the arithmetic and weighted means decrease

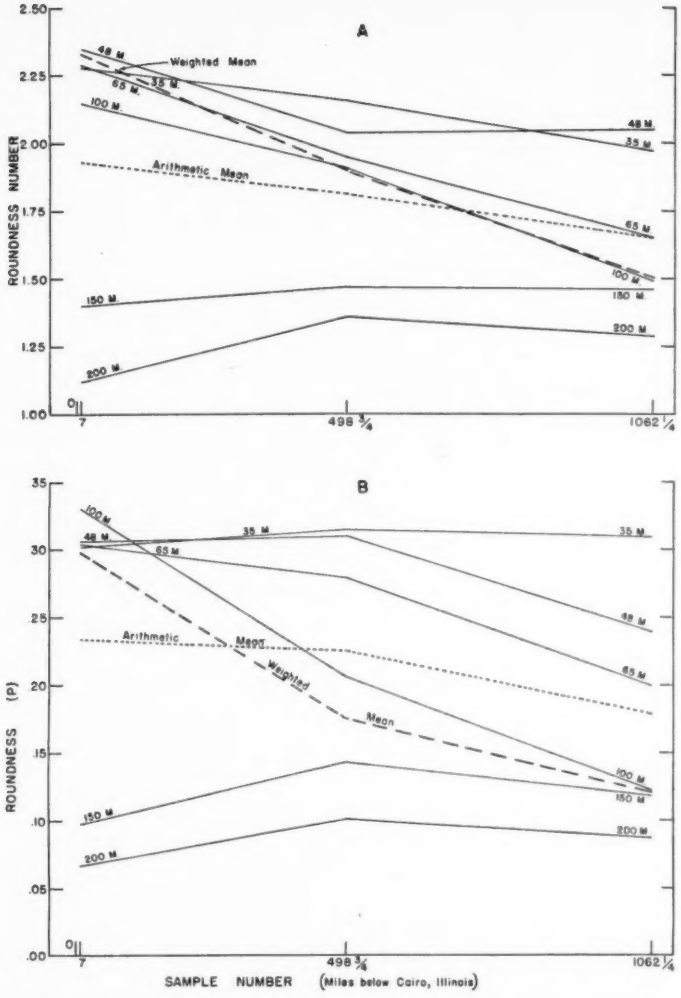

FIG. 9.—Relationship between roundness and distance downstream; comparison of the *P* values with the roundness numbers of the same samples.

downstream. The decrease, however, is not so striking as is the decrease in roundness values.

INTERPRETATION OF DATA

There appear to be three possible explanations of the downstream decrease in roundness shown by the samples studied. These are: (1) progressive changes in mineral composition; (2) a progressive sorting on the basis of shape; and (3) fracturing of the grains. A progressive downstream decrease in the amount of feldspar present in the 100-mesh grade of the Mississippi River sands has been

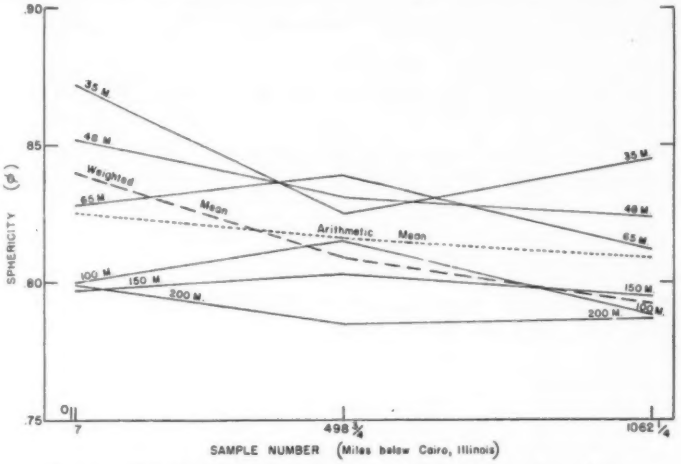

FIG. 10.—Relationship between sphericity (ϕ) and distance downstream

demonstrated.[49] In view of the relationship between quartz-feldspar ratio and roundness (p. 252 and Fig. 7) this loss of feldspar, and consequent relative increase in the amount of quartz, would result in decreased roundness values. The decrease in feldspar content is very slight, however. In the 100-mesh grade the feldspar decrease between Cairo and the Gulf represents only about 5 per cent of the average sample (approximately one-fifth of the total feldspar). This appears insufficient to explain the decrease in roundness. The feldspar, moreover, is most abundant in the finer size grades,[50] so that loss of feld-

[49] "Mineral Composition of Mississippi River Bed Materials" (awaiting publication).

[50] "The Size Distribution of Minerals in Mississippi River Sands," *loc. cit.*

spar should be accompanied by a greater decrease in roundness of the finer grades than of the coarser. As has been shown, actual conditions are exactly opposite; the coarser grades show the decrease in roundness. Finally, study of the whole samples shows no evidence of a decrease in feldspar content.[51] This is due to the fact that the downstream decrease in the mean grain size of the samples results in a higher percentage of the finer size grades, which contain more feldspar. This factor offsets the decrease in feldspar content of the individual size grades, so that the whole samples maintain a nearly constant feldspar percentage from Cairo to the Gulf. There is, however, a decrease in roundness of the whole samples. It therefore seems justifiable to conclude that decrease in feldspar content will not explain the decrease in roundness, though possibly it is a contributing factor.

A predominance of either the suspension or the traction (rolling) type of movement results in a progressive sorting on the basis of shape.[52] If rolling predominates, grains of high sphericity, which roll more easily, outrun the others and thus become progressively more concentrated in the direction of movement. When suspension predominates, the less spherical grains, which possess a greater area with respect to their volume, move down current more rapidly than those of higher sphericity, resulting in a downstream decrease in the mean sphericity of successive samples. Now a general relationship between roundness and sphericity has been demonstrated (pp. 247–48 and Fig. 5); that is, the rounder grains usually possess higher sphericity values. This is especially true of grains ranging from angular to subrounded, and almost all the grains of the Mississippi River sands fall within this range. If, then, the suspension type of movement predominates in the river, the samples would show not only a downstream decrease in sphericity but a decrease in roundness as well. On the other hand, a decrease in roundness, due to fracturing or other causes, might be accompanied by a decrease in sphericity. This does not necessarily follow, since grains of low sphericity, especially flat grains, might become more spherical as a result of being broken up into smaller fragments. Grains whose initial

[51] "Mineral Composition of Mississippi River Bed Materials" (awaiting publication).

[52] Wadell, "Volume, Shape, and Roundness of Rock Particles," *loc. cit.*

sphericity is fairly high, however, would become somewhat less spherical as a result of fracturing.[53] The Mississippi sands possess fairly high sphericity values; the three coarsest grades analyzed from sample M-7, for example, have an average sphericity of 0.851, somewhat greater than the corresponding sizes of the St. Peter sand analyzed by Wadell.[54]

The problem thus becomes essentially one of relative cause and effect. Is the decrease in roundness shown by the Mississippi River samples simply a reflection of a decrease in sphericity, resulting from sorting on the basis of shape, or is the decrease in sphericity only an accompaniment of a decrease in roundness caused by fracturing or other factors? Some evidence on this point is available from the actual amount of decrease in each case. The arithmetic means of the ϕ values show a decrease of 0.016 (0.825 to 0.809), or 1.9 per cent, while the arithmetic means of the P values decrease by 0.055 (0.239 to 0.179), or 23.5 per cent. The weighted mean values show greater decreases as a result of the effect of the downstream increase in percentage of the smaller grains, which possess lower roundness and sphericity values. The decrease in sphericity is 0.058 (0.840 to 0.792), or 6.9 per cent, while the decrease in roundness is 0.179 (0.298 to 0.121), or 60 per cent. The roundness numbers calculated from the data from the visual method show decreases slightly less than those shown by the Wadell P values. The decrease in the arithmetic means is 0.28 (1.93 to 1.65), or 14.5 per cent, while the weighted means decrease by 0.83 (2.33 to 1.50), or 35.6 per cent. The weighted means of the roundness numbers are not exactly comparable to those of the Wadell values, however, as the former were calculated on the basis of the weight percentage of material in each size grade, while frequency values were used in computing the weighted means of the Wadell data. Calculating weighted means for the Wadell P values in the same manner as for the roundness numbers, we secure the following figures for the three samples, in downstream order: 0.305, 0.205, and 0.134. This is a decrease of 0.171, or 56 per cent. Even if the first three and last three samples analyzed

[53] Lamar's "relative angularity" figures (actually a measure of sphericity) are markedly lower for artificially crushed Cypress sand than for uncrushed St. Peter sand (Lamar, *op. cit.*, p. 151).

[54] Wadell, "Volume, Shape, and Roundness of Quartz Particles," *loc. cit.*

by the visual method are averaged to reduce the effects of local variations, the decrease in the weighted means of the roundness numbers is 0.53 (2.29 to 1.76), or 23.1 per cent. In other words, the decrease in roundness shown by the samples is between five and ten times as great (on a percentage basis) as the decrease in sphericity. This suggests that the decrease in roundness is the primary effect and that the decrease in sphericity results from the decrease in roundness. The roundness and sphericity values are not directly comparable, however; hence there is a possibility that the much smaller decrease in sphericity values is just as important as the larger decrease in roundness. Studies of other progressive changes of this type should determine this point.

Evidence presented by MacCarthy[55] and by Pettijohn and Ridge[56] indicate that a progressive sorting on the basis of shape occurs in beach sands moved along a coast by currents. The movement is dominantly by suspension, with the result that grains of low sphericity are concentrated down beach (in the direction of the current). As has been stated, MacCarthy's "roundness" values are actually a measure of sphericity. Moreover, they are almost identical with Wadell's ϕ values, as may be seen by computing both values for various geometrical shapes and comparing them. Though MacCarthy does not give arithmetic means of the samples, they may be computed from his data. In 128 miles of travel down the beach, the decrease in the arithmetic means of the sphericity values is 0.048 (0.874 to 0.826), or 5.5 per cent, while the corresponding value for the Mississippi samples is 0.016 (0.825 to 0.809), or 1.9 per cent. MacCarthy's "crude roundness" values are weighted means computed on the basis of the weight percentage of material in each size grade. They show a decrease of 0.064 (0.891 to 0.827), or 7.2 per cent. Computing the equivalent values for the Mississippi River samples, we find the decrease to be 0.055 (0.847 to 0.792), or 6.5 per cent. In other words, transportation for more than 1,050 miles in the Mississippi River does not produce so great a decrease in sphericity as does 128 miles of travel down a beach. This appears to be conclusive evidence that sorting on the basis of shape is not adequate

[55] "The Rounding of Beach Sands," *loc. cit.*

[56] F. J. Pettijohn and J. D. Ridge, "A Mineral Variation Series of Beach Sands from Cedar Point, Ohio," *Jour. Sed. Petrol.*, Vol. III (1933), pp. 92–94.

to explain the decrease in roundness shown by the samples from the river.

An objection to this conclusion might be raised on the basis that the data on sphericity are based on the analysis of only three samples; hence it is possible that the actual decrease is somewhat greater than that shown. This appears unlikely, however, in view of the fact that the percentage decrease in roundness (P) values, shown by these same samples, is somewhat greater than the average percentage decrease shown by all the samples analyzed by the visual method. Probably the decrease in sphericity shown is therefore at least as great as that actually occurring in nature. This conclusion is supported by the fact that the intermediate and larger sizes show the principal decrease in sphericity. If sorting on the basis of shape is effective, the smaller sizes should show the greatest downstream decrease in sphericity, since there is a greater tendency for them to travel by the suspension type of movement than there is for the larger grains. The latter, being nearer the upper limit of size transportable under given conditions of velocity and turbulence, would tend to move more by traction (rolling). The finer sizes, however, maintain essentially constant sphericity values.

These facts strongly suggest that sorting on the basis of shape is a relatively unimportant factor in the transportation of the sand constituents of the Mississippi River's bed load, and certainly no more than a contributing factor to the downstream decrease in roundness of the sands. As has been mentioned elsewhere,[57] this is what might be expected in streams, for conditions of velocity and turbulence fluctuate so greatly from time to time and from place to place in a stream's bed that a considerable range of sizes would be moved about equally by suspension and by traction. Within this range, little or no sorting on the basis of shape would take place.

Since changes in mineral composition and sorting on the basis of shape appear inadequate to explain the downstream decrease in roundness of the larger grains, this condition would seem to be chiefly due to fracturing and chipping. There is positive evidence that this is the case. It has been mentioned previously (p. 240) that all freshly fractured grains were placed in the angular group in

[57] "Mineral Composition of Mississippi River Bed Materials" (awaiting publication).

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[57] "Mineral Composition of Mississippi River Bed Materials" (awaiting publication).

analyses by the visual method. As a matter of fact, this group consists almost exclusively of grains bounded partially to completely by freshly broken, clear surfaces. Most of the grains in the other roundness groups show the polished surfaces typical of sands transported by water, but fractured grains on which the broken surface had become polished were not considered as "freshly fractured" and were not placed in the angular group. The percentage of grains in this group thus affords evidence of the importance of fracturing and chipping during transportation downstream. This information is presented in Figure 11. The data agree with the roundness numbers in indicating that the character of the tributary samples does not have an appreciable effect upon samples from the Mississippi immediately below the mouths of the tributaries. Tributary samples were therefore omitted in plotting Figure 11, and near-by samples were averaged so that the graph might be condensed.

In Figure 11 the two finer size grades (150- and 200-mesh) are separated by a gap from the three coarser grades (35-, 48-, and 65-mesh). The values for the 100-mesh grade fluctuate back and forth, within this zone of separation, to such an extent that any slight progressive changes which might be present are obscured. The two finer-size grades maintain nearly constant values, with a suggestion of a slight decrease, while the three coarse grades show an obvious downstream increase in the percentage of angular (freshly fractured) grains. If Figure 8, showing downstream changes in the roundness of the samples, were reversed horizontally and vertically and compared with Figure 11, the similarity between the two would be very striking. One is led irresistibly to the conclusion that fracturing and chipping are the chief causes of the decrease in roundness of the coarser size grades.

The amount of fracturing indicated by Figure 11 actually is a minimum value. When only one or two fractures are present on a grain, it frequently lies so that these are hidden, in which case the grain is placed in a higher roundness group on the basis of the surface exposed. When the grains are turned over and examined in several positions, the number of grains with freshly broken surfaces is found to be much higher. This was done for the 35-mesh grade of each sample. The percentage of grains with fresh fractures was found to range from about 25, in the samples immediately below Cairo, to

40 and over in those from New Orleans and below; nearly twice as high as percentages determined by counting the grains without moving them. Moreover, the downstream increase shown by Figure 11 also is a minimum value. It seems improbable that a freshly broken surface would remain clear and glassy after more than a

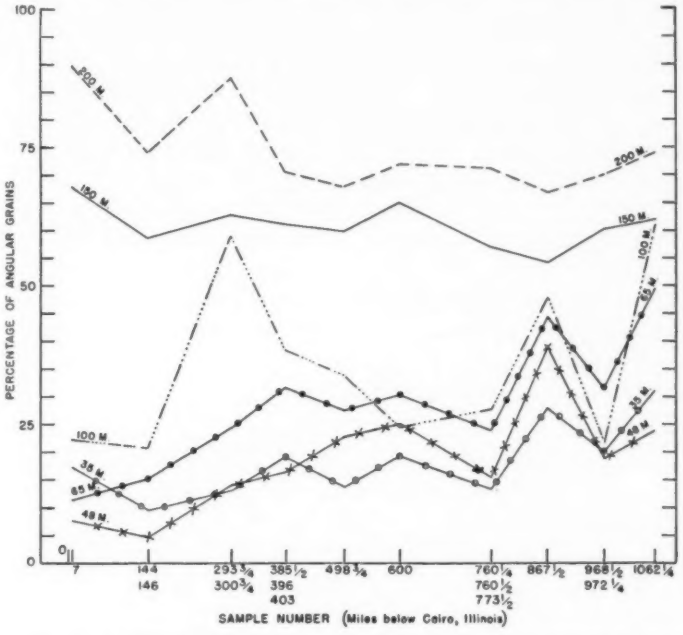


FIG. 11.—Relationship between percentage of angular (freshly fractured) grains and distance downstream.

thousand miles of travel; at least some dulling or "polishing" probably would take place. There is, in fact, some evidence that the "polished surface" develops rather rapidly. Fractures whose originally sharp edges are barely dulled often show good "polishing." This feature also appears to be developed almost as well on flat and concave surfaces as on corners and edges—a fact which suggests that it may be the result of solution, as indicated by Galloway.[58] There exists a possibility, therefore, that fractures which are "fresh" at

[58] Galloway, *op. cit.*

Cairo are no longer so below New Orleans. If this is true, the difference between the percentages of freshly fractured grains at Cairo and the percentages of freshly fractured grains below New Orleans does not represent the total amount of fracturing taking place during the journey from Cairo to New Orleans. The percentage of such grains in samples from below New Orleans would more closely approximate the actual amount of fracturing taking place during this journey.

It should be remembered, in view of the foregoing discussion, that the decrease in roundness is slight in comparison to the downstream decrease in size of grain shown by mechanical analyses. Though the three coarsest size grades studied definitely become more angular downstream, the change certainly is not sufficient to explain the downstream decrease in the mean grain size of Mississippi River bed materials. The latter must be chiefly due to sorting on the basis of size, the larger particles being left upstream as a result of a progressive decrease in the transporting ability of the river. Reduction in size by fracturing and chipping is a contributing factor, but apparently one of minor importance.

SUMMARY AND CONCLUSIONS

Studies of sand samples collected from the bed of the Mississippi River at intervals from Cairo to the Gulf, and of samples from the principal tributaries in this stretch of the river, show that:

1. There is a decrease in both roundness and sphericity with decreasing size of grain. This relationship, however, applies to the average of a number of samples and is not always applicable to individual samples.

2. There is no obvious correlation between the abundance of a particular size and its degree of roundness or sphericity.

3. There appears to be a relationship between mineral composition and roundness. Higher quartz percentage (lower feldspar content) is usually accompanied by a somewhat lower roundness value.

4. The sand sizes studied (0.589–0.074 mm. diameter) show no evidence of becoming rounded during transportation by the river. On the contrary, the larger sizes (0.589–0.208 mm.) become slightly more angular downstream. The evidence indicates that this condition is chiefly due to fracturing and chipping of the grains. A downstream decrease in the feldspar content of individual size grades of

the samples, and sorting on the basis of shape, may be contributing factors. If so, they apparently are of minor importance.

Grain size seems to be one of the factors determining the effects of attrition in streams. Below a certain size (between 0.208 and 0.147 mm. diameter in the lower Mississippi) the grains are little affected, probably because their mass is so slight that the force of impact against one another and against the channel walls is not sufficient to produce fracturing, and rounding takes place too slowly to be very evident. Above this size, the grains become progressively more angular downstream as a result of fracturing and chipping. Pebbles, however, apparently become rounder during stream transportation in most cases. There must, then, be an upper size limit above which fracturing and chipping do not result in more angular particles but, on the contrary, particles become rounder. In the Mississippi this upper size limit is greater than 0.589 mm. diameter. Unfortunately it is not possible to fix its value more definitely on the basis of available data.

The limiting sizes mentioned above undoubtedly vary from stream to stream, and even from place to place within an individual stream, depending upon the rigor of abrasive action. Conditions of attrition in the lower Mississippi River, however, probably are no more rigorous than in most streams and certainly less so than in streams with steep gradients and high velocities. With more rigorous attrition, fracturing and chipping would produce a greater decrease in roundness than that shown by the Mississippi sands. Moreover, the upper size limit of this action would be greater; that is, still larger grains would fall within the range of sizes whose roundness decreases downstream as a result of fracturing and chipping. The belief that streams characteristically round their transported sands therefore seems to be without foundation. Apparently this concept is another armchair theory developed without the support of evidence from actual observations.

ACKNOWLEDGMENTS.—The writers wish to express their appreciation to the Graduate School of Louisiana State University for financial assistance. To their colleagues in the School of Geology, Louisiana State University, they are indebted for much valuable criticism and advice. Dr. Hakon Wadell contributed a copy of his paper "Volume, Shape, and Roundness of Quartz Particles" prior to its appearance in print. The samples were furnished by the Mississippi River Commission.

THE STRUCTURAL GEOLOGY OF THE LIVINGSTON PEAK AREA, MONTANA

EDWARD C. H. LAMMERS
Washington and Lee University

ABSTRACT

The Laramide structures in and adjacent to the northwestern corner of the Beartooth Mountains are described. During the early stage of the orogeny the North Snowy block of the Beartooth Range was upthrust by deep-seated compressive stresses. In the later stage a large southward-advancing overthrust sheet encountered the corner of the North Snowy block and was deformed by lateral shearing stresses set up within it. Pressure-box experiments are described in which the later-stage structures of the Livingston Peak area were duplicated in almost every detail.

INTRODUCTION

In southern Montana and northwestern Wyoming the bold Beartooth Mountain Range rises abruptly from the broad plains of central Montana and from the more limited Bighorn basin, which is a southward embayment of the Great Plains, into the Northern Rocky Mountains. It is an arcuate uplift, whose general trend is northwest and southeast. No less imposing than its plains-facing northeast front is the western face of the range, rising steeply from the valley of the Yellowstone River. On the south and southwest the range is bounded by the Yellowstone Park structural basin, into which has been ejected an enormous amount of Tertiary volcanic material subsequently carved by erosion into the precipitous peaks of the Absaroka Mountains. Topographically and geologically the range is a unit, and one of the most important units in the structural framework of the Bighorn basin. Because it affords exceptional opportunities for studying one type of mountain-building and because of its richness in problems in many related fields, the Beartooth Range was chosen in 1930 by a group of co-operating geologists as a desirable place for intensive geological research.

The ultimate aim of this co-operative project was a better understanding of the structural development and history of this portion of the Rocky Mountains. As a part of the research program, small key areas were studied and mapped in detail by individual members of

the group, to be fitted together later in a general monograph on the whole region. Thus in July, 1933, the writer, at the suggestion of Drs. Chamberlin, Thom, and Bucher, began a study of the structure of the northwestern corner of the Beartooth Range.

The area mapped, which covers about 70 square miles, is the northwest end of the Beartooth Range between the Great Plains around Livingston, Montana, and the drainage basin of the Deep Creek tributary of the Yellowstone River on the south, and extending from a few miles west of the Yellowstone to the eastern side of

FIG. 1.—Looking southward from Mount Baldy. Graham Pass is in the foreground

Mission Peak, one of the highest points in this part of the range. It has been named the Livingston Peak area after the barren limestone peak of that name, which forms a prominent landmark for travelers approaching the range from the north. Most of the area is in the high range, but it also includes the ridges and lowlands lying immediately north and west of the mountains. The city of Livingston lies about a mile north of the boundary of the area.

During the first summer the writer, in collaboration with Dr. Donald MacNeil and Dr. Dorr Skeels, of Princeton University, mapped the portion of the area lying west of the Yellowstone River. Assisted by Mr. Charles MacClintock, of the University of Illinois, the writer mapped the remainder in the field seasons of 1934 and 1935.

STRATIGRAPHY

The formations outcropping in the district are listed in Table 1. A complete section was not measured by the writer because accurate

TABLE 1

COLUMNAR SECTION OF THE NORTHWESTERN CORNER OF THE BEARTOOTH MOUNTAINS

System	Formation	Thickness in feet
Quaternary	Alluvium Glacial drift	.....
Cretaceous	Eagle formation Telegraph Creek–Niobrara–Carlile shales Frontier sandstone Mowry-Thermopolis shales Dakota sandstone (?) Fuson shale (?) Lakota conglomerate (?)	408* 1593* 300* 895* 88* 260* 104*
Jurassic	Morrison formation Sundance formation	228* 484*
Pennsylvanian	Tensleep quartzite	140†
Mississippian	Amsden formation Madison limestone	111† 1800
Devonian	Three Forks–Jefferson formation	514‡
Ordovician	Bighorn dolomite	438‡
Cambrian	Gallatin limestone Gros Ventre shale Flathead quartzite	518‡ 290 180
Pre-Cambrian	Quartzites, gneisses, and schists	.....

* Measured by C. W. Wilson, Jr., near Gardiner, Montana; cf. his "Geology of the Thrust Fault near Gardiner, Montana," *Jour. Geol.*, Vol. XLII (1934), pp. 651–52.

† Measured by H. W. Scott in the Lower Canyon of the Yellowstone River; cf. his "Studies on the Quadrant Group of Montana and Wyoming," Unpublished Doctor's thesis, Department of Geology and Paleontology, University of Chicago (1935), p. 34.

‡ Measured by C. W. Tomlinson on the ridge between Livingston Peak and Mount Baldy; cf. his "Paleozoic Stratigraphy of the Rocky Mountains," *Jour. Geol.*, Vol. XXV (1917), pp. 118–19.

measurements of most of the formations found in the area have already been made by other geologists working in the vicinity. Furthermore, structural deformation has caused considerable variation in the thickness of certain formations, and scarcity of well-exposed sections prevents a satisfactory measurement of some others.

GENERAL REGIONAL STRUCTURE

The Beartooth Range is an arcuate structural uplift comparable in size to the Bighorn Mountains of Wyoming. The low-angle Beartooth thrust fault, which dips beneath the range along its northeastern front, and the high-angle Gardiner thrust, which dips beneath the southwest corner of the range, give to the Beartooth Mountains the appearance of a typical wedge-shaped uplift. When studied in detail, however, the range is found to be not a simple uplift but a composite uplift consisting of three well-defined units or blocks. During the uplift the North and South Snowy blocks, which make up the western third of the range, were tilted to the northeast, whereas the larger Beartooth Plateau block, which forms the central and southeastern parts of the range, was tilted to the southwest. As a result of this differential tilting there is a reversal in the asymmetry of the range at the northwestern edge of the Beartooth Plateau block. Without exception the minor structures have the same asymmetry as that of the block with which they are associated.

The North Snowy block is the most sharply defined of all the blocks. Along its western side it is bounded by a high-angle normal fault, well exposed at its northern end but passing beneath the alluvium of the Yellowstone Valley farther south-southwest. Elevation of the block along this fault is greatest at its southern end near the mouth of Mill Creek, about 25 miles south of Livingston. The block is separated from the South Snowy block on the southwest and the Beartooth Plateau block on the southeast by a zone of high-angle faults, which trends approximately east and west from the mouth of Mill Creek to the Stillwater River Canyon on the northeast front of the mountains, about 40 miles east-southeast of Livingston. Toward the eastern end of this fault zone the North Snowy block has been depressed with respect to the adjoining Beartooth Plateau block, which was tilted in the opposite direction. Toward the western end of the fault zone it has been elevated above the neighboring South Snowy block. On its northeast side the dip slope of the North Snowy block and those of the associated minor structures form an irregular mountain front facing the plains. The area considered in this report lies partly in the northwest corner of the North Snowy block and partly immediately to the north and west of it.

DESCRIPTION OF THE STRUCTURES IN THE AREA

GENERAL

Every one of the structures mapped in the Livingston Peak area was formed either directly or indirectly by lateral compression during the Laramide revolution. Folding, faulting, and lateral shifting were the chief processes involved, with faulting predominant. The deformation occurred in two distinct stages. During the earlier stage compressive stresses, acting at considerable depth, thrust up the Beartooth Range and tilted its component blocks. Later other stresses, operating nearer the surface, produced the minor folded and faulted structures adjacent to the range.

FAULTS

The major normal fault, separating the North Snowy block from the region of low structural relief west of it, was formed in the early stage of deformation. This fault, which is the only normal fault in the district, owes its inception to vertical stresses set up by deep-seated compression. During the later stage a large plainsward-dipping overthrust was developed, whose hanging-wall block has ridden up and around the northwestern corner of the range. Where the forward advance of this overthrust sheet was stopped by the range, secondary high-angle thrusts were developed within the sheet north of the main fault. The only thrust fault in the area to form in front of it lies west of the mountains and has no continuation across the normal fault bounding the range. One of the two tear faults in the area resulted from the differential forward movement of the hanging-wall block of the major thrust. The other was formed during the folding of an anticline, which was subsequently faulted by one of the larger secondary thrusts. The details of the fault pattern are too complex to be easily described. For these details the reader is referred to the geologic map of the area.

Deep Creek Ridge normal fault.—Although actually traceable for only $1\frac{1}{2}$ miles from Deep Creek across Deep Creek Ridge to Suce Creek, this is one of the most important faults in the region. From Deep Creek to the summit of Deep Creek Ridge the trace of the fault trends N. 25° E. Northward, the trace swings steadily to the the west until at Suce Creek its trend is N. 35° W. Where measure-

ments could be made, the dip of the fault plane was found to vary from 80° W. to vertical. Thus the arcuate trace of the fault is dependent upon change in strike rather than upon variation in topography. The eastern side of the Deep Creek Ridge fault has been uplifted relative to the western, bringing pre-Cambrian schists and gneisses in contact with the Madison limestone. To the north the fault is cut off by the Suce Creek thrust fault, while to the south it disappears beneath the Deep Creek terminal moraine.

South of the point where Deep Creek flows into the Yellowstone River, the Yellowstone Valley has a nearly straight south-southwest trend for over 15 miles. East of it lie the lofty pre-Cambrian mountains of the North Snowy block, whereas west of it there are only comparatively low ridges of Paleozoic and Mesozoic sedimentary rocks, which are largely covered by thick accumulations of Tertiary volcanic breccias and tuffs. These ridges are not normal hogback ridges dipping away from the high part of the Beartooth Range but are expressions of independent structures, which strike into the valley and hence lie at an angle to the front of the range. If the strike of the southern end of the Deep Creek Ridge fault were to be continued south-southwestward, the trace of the fault would lie beneath the alluvium of the Yellowstone Valley about a mile west of the western front of the range. Since an extension of this fault would not only logically explain the differences in the rocks on either side of the Yellowstone Valley, for many miles south of the area, but would also account for the abrupt western termination of the Beartooths, it has been extended to the southern boundary of the map.

Suce Creek–Window thrust.—This fault, which extends across the area in a general east-and-west direction, is the most important thrust fault in the region. It was formed after the main uplift of the range, for it cuts off the Deep Creek Ridge fault along which the North Snowy block was tilted. Along the eastern extent of the fault, where the forward shove encountered the western extremity of the Beartooth Range, the hanging-wall block of the thrust has ridden a short distance up the dip slope of the North Snowy block, whereas west of the retarding Beartooth buttress the thrust sheet has advanced unobstructed over a region of low structural relief. As a re-

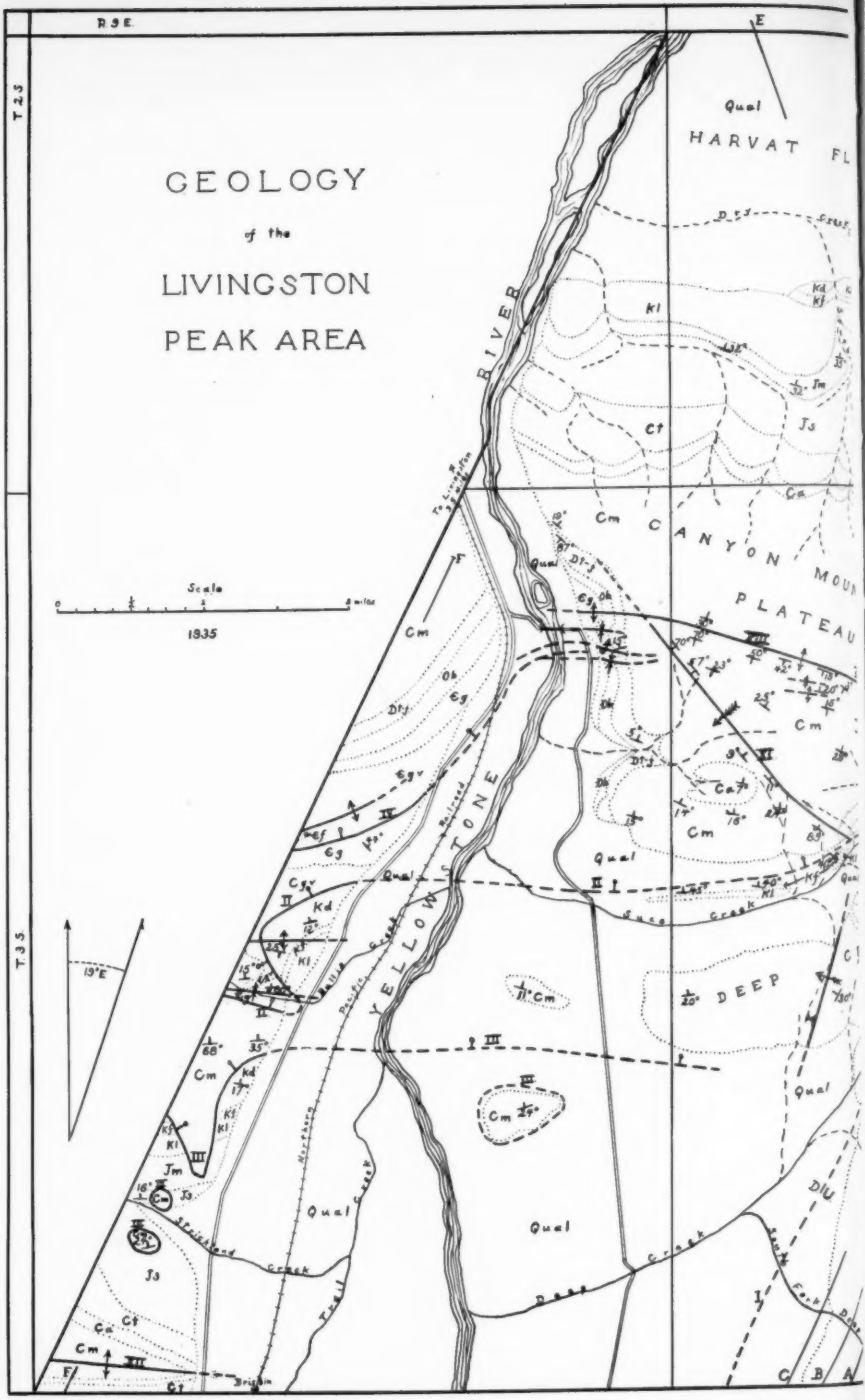
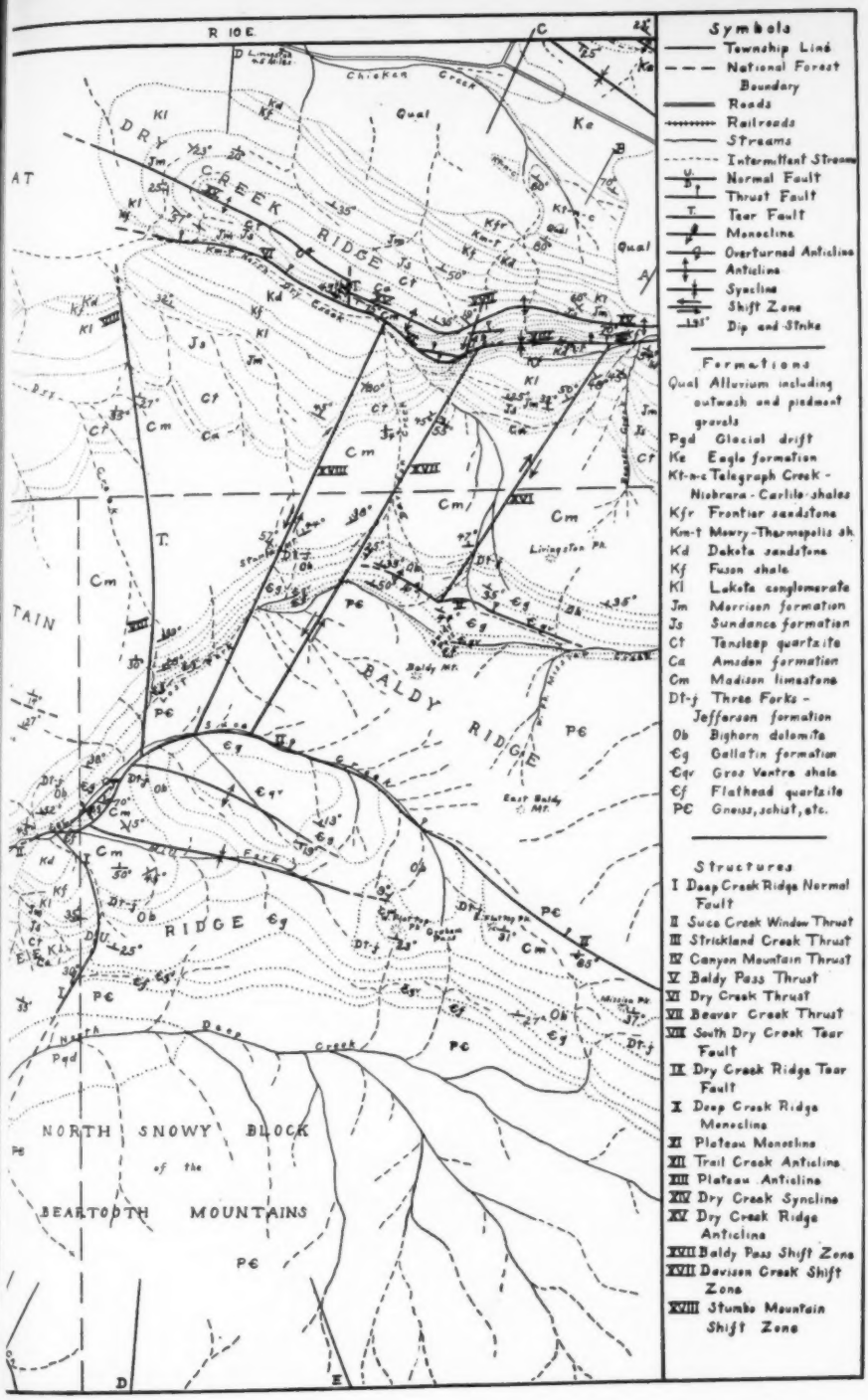


FIG. 2.—Geology of the



Livingston Peak area

sult of this buttress in the foot wall of the thrust, actual displacement along the fault increases from east to west. The effect of the buttress is also manifest in great differences in the strikes and dips of the eastern and western sections of the fault.

West of the Yellowstone River, where it is known as the Window thrust, it is an extremely low-angle fault. At the mouth of Bullis Creek the Gallatin limestone has been thrust onto the Upper Madi-

FIG. 3.—The trace of the Suce Creek thrust fault. The upper part of the slope is underlain by dark-colored schists and gneisses of pre-Cambrian age, the lower slope by light-colored Madison limestone.

son limestone. North of Bullis Creek a post-thrust upwarp combined with subsequent erosion has caused the formation of a very large fenster, exposing the Mesozoic Lakota, Fuson, and Dakota formations surrounded by the Gallatin and Gros Ventre beds of the Cambrian. Although the upwarp has somewhat modified the original dip of the fault plane, it can be safely stated that the dip of the western section of the Suce Creek–Window thrust fault, even before warping, was not in excess of 15° N.

East of the Yellowstone Valley the trace of the thrust follows the main fork of Suce Creek to its headwaters north of East Flattop Mountain and thence follows the southern slope of Baldy Ridge to the eastern boundary of the area. Near East Flattop Mountain the

fault strikes N. 70° W. and has an apparent dip of about 55° N. The stratigraphic displacement along this part of the fault varies greatly as a result of the differential forward movement of the several sections of the hanging-wall block.

Strickland Creek thrust.—Another thrust fault of large stratigraphic displacement, but of less importance, is the Strickland Creek thrust, which comes to the surface north of Strickland Creek. It is similar in strike and dip to the western section of the Suce Creek–Window thrust. The upper block of the fault, which is entirely composed of Madison limestone, has overridden several Mesozoic formations.

Canyon Mountain thrust.—This fault differs from the other thrusts west of the Yellowstone River in having a steeper dip and a smaller stratigraphic displacement. Although the fault plane cannot be actually observed, the comparative regularity of its trace across the south slope of Canyon Mountain indicates that the fault is not a typical low-angle thrust. Where the displacement is greatest, the Gros Ventre formation has been thrust onto the Upper Gallatin limestone.

Baldy Pass thrust.—Located less than a half-mile northeast of Baldy Pass, this fault resembles the Canyon Mountain thrust in many ways. It is a high-angle thrust of small displacement involving only Cambrian formations.

Dry Creek and Beaver Creek thrusts.—Striking parallel to the Baldy Pass thrust and lying northwest of it is the Dry Creek thrust, which has been traced from the southeastern corner of Harvat flat about 2 miles up the valley of Dry Creek to where it passes into the Dry Creek syncline. Like the Baldy Pass thrust and the eastern section of the Suce Creek–Window thrust it is a high-angle fault. The Beaver Creek thrust is essentially a continuation of the Dry Creek fault to which it is linked by the Dry Creek syncline.

South Dry Creek tear fault.—Named because it lies almost entirely within the drainage basin of the south fork of Dry Creek, this fault strikes north and south and has a nearly vertical dip. Its trace runs northward from the valley of Suce Creek over the ridge between Livingston Peak and Canyon Mountain to the southeastern corner

of Harvat flat. The tear is limited to the Suce Creek thrust sheet and was formed at the time of thrust faulting.

The western side of the South Dry Creek tear fault has moved south relative to its eastern side. As a result of this movement the actual displacement on the Suce Creek thrust fault is decidedly greater west of the tear than east of it. The difference in crustal shortening on the two sides of the tear, arising from this differential displacement on the thrust, is equalized farther north by the Dry Creek Ridge anticline, which plunges westward at the eastern edge of Harvat flat and hence just east of the northward extension of the tear beneath the gravels of the flat.

Dry Creek Ridge tear fault.—This fault was formed during the folding of the Dry Creek Ridge anticline. When folding occurred, the section of the anticline west of the tear was relatively less compressed than the section east of it, the change in the amount of compression taking place at the fault. The Dry Creek Ridge tear has been cut off at its southern end by the Dry Creek thrust, and hence is known to be older than that structure.

FLEXURES AND FOLDS

During the early stage of the orogeny two monoclines were formed in the Livingston Peak area. One of these is the structural continuation of the Deep Creek Ridge normal fault north of the trace of the Suce Creek thrust. The other, which lies south of the trace of the thrust, parallels the normal fault. In the later stage of deformation several anticlines and synclines, a broad upwarp, and a downwarp were produced by shallow compressive stresses.

Plateau and Deep Creek Ridge monoclines.—Striking N. 40° W. the Plateau monocline has been traced from the Suce Creek thrust fault across Canyon Mountain Plateau to the Lower Canyon of the Yellowstone River. For the following reasons it is believed that this monocline was once continuous with the Deep Creek Ridge normal fault. The strike of the flexure is nearly the same as that of the northern end of the fault. The displacement on the two structures is similar not only in direction but also in amount. The displacement on the normal fault at its intersection with the Suce Creek thrust is so large as to necessitate a continuation of the structure north of the thrust.

The Deep Creek Ridge monocline parallels the Deep Creek Ridge fault and was probably formed by the same stresses. This flexure has a small displacement and there is no continuation of it north of the trace of the Suce Creek thrust.

Trail Creek anticline.—In the southwestern corner of the area a high limestone ridge projects into the Yellowstone Valley, the crest of which is formed by the core of an asymmetrical anticline. It has been named the Trail Creek anticline for the stream which flows along its southern flank west of the area, where it has been overturned and thrust-faulted.

There is at present a decrease in the intensity of deformation southward from the trace of the Suce Creek–Window thrust: the Strickland Creek thrust fault has a measurable displacement of almost a mile; the Trail Creek anticline has locally been ruptured by a thrust fault of considerably less displacement; no thrust fault is known to occur south of this fold. Hence it is believed that the folding and faulting south of the trace of the Suce Creek–Window thrust fault were probably caused by the southward advance of the hanging-wall block of this thrust.

Open folds on the dip slope of the North Snowy block.—In the southern part of the Suce Creek drainage basin, on the dip slope of the North Snowy block, are located a broad low anticline and a syncline. The strike of these folds is parallel to the average strike of the four thrust faults east of the Yellowstone River. Both folds are most compressed near their western ends. The actual displacement on the Suce Creek thrust also increases westward. These similarities strongly suggest that the folds, like the Trail Creek anticline, were formed by the unbalanced stresses involved in the forward movement of the Suce Creek–Window overthrust sheet.

Dry Creek syncline.—Striking east and west, this structure links the Dry Creek thrust fault to the Beaver Creek thrust. The beds forming the northern limb of the syncline have been thinned to less than one-third of their original thickness by stretching, which resulted from the thrusting that produced the Dry Creek and Beaver Creek thrust faults. The beds on this limb vary in dip between 70° S. and vertical, while those on the southern limb dip 30° N.

Dry Creek Ridge anticline.—This anticline, which holds up Dry Creek Ridge, is a very complex structure. From west to east it

passes from a broad open anticline into a nearly isoclinal fold. The structure has been thrust-faulted to the south at both ends, and where thrust faulting has not occurred, the southern limb of the fold has been stretched and thinned by the thrusting.

Warping west of the Yellowstone River.—West of the Yellowstone River near the mouth of Bullis Creek an upwarp and a downwarp have deformed the fault plane of the Suce Creek–Window thrust. The downwarp controls the course of Bullis Creek. The upwarp lies north of this creek and is partially responsible for the large fenster in the thrust sheet, which exposes the Lakota, Fuson, and Dakota

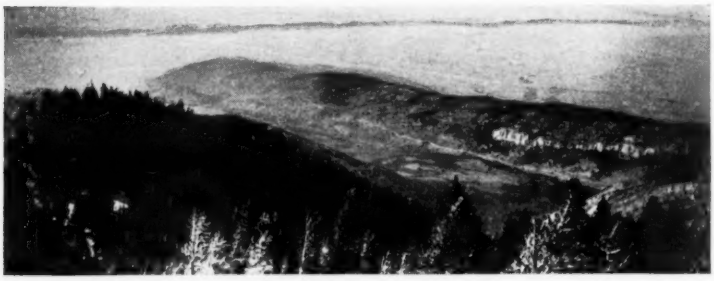


FIG. 4.—The western end of the Dry Creek Ridge anticline

formations surrounded by the Gallatin limestone and the Gros Ventre shale.

Since the fault plane prior to warping probably had a fairly uniform northward dip, the upwarp must be asymmetrical in cross section, its southern limb having the steeper dip. From the cross section of the upwarp something can be learned as to the nature of the stress which produced it. The structure was probably formed by a force couple in which the higher force was directed toward the south. As a movement on the Canyon Mountain thrust fault, whose trace lies a short distance north of the upwarp, would set up a force couple of this type, it is believed that the warping resulted from the southward advance of the Canyon Mountain thrust sheet.

The downwarp is so closely related to the upwarp that little need be said about it. It, too, is asymmetrical in cross section and was doubtless formed by the same stress that produced the upwarp.

SHIFT ZONES

"Shift" is a general term used to describe the displacement of masses on either side of a complicated shear or fault zone, better termed a "shift zone." The three zones in the Livingston Peak area are homologous to tear faults, the only difference being that in the case of tear faults shearing takes place on a single plane, whereas in the case of shift zones shearing is distributed throughout a zone bounded by two parallel planes.

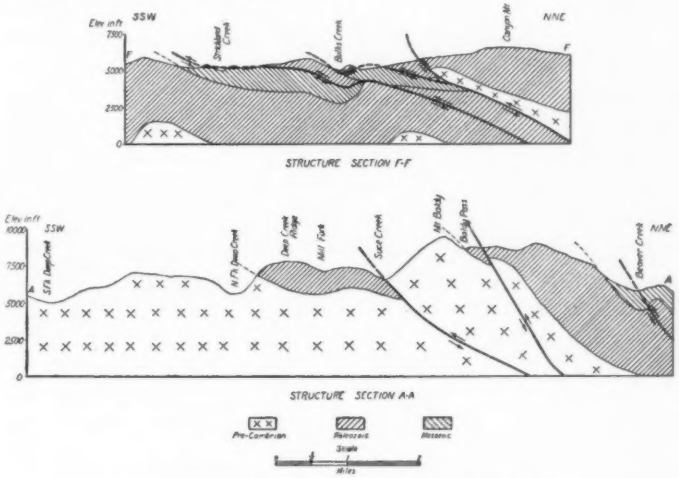


FIG. 5.—Structure sections in the Livingston Peak area

Certain characteristics of these zones make them easily discernible in the field. At the edge of a zone there is a change in the strike of the beds involved. Within the zone the less competent shales and sandstones have been thinned by stretching, and the more competent limestones and quartzites have been brecciated and displaced by numerous very small faults. The lines on the map (Fig. 2) showing the strikes and positions of the zones, which are mostly only a few hundred yards wide, were drawn as nearly as possible through the middle of each zone.

Baldy Pass shift zone.—This shift zone, which strikes N. 35° E., extends from the western end of the Baldy Pass thrust fault north-

eastward to the Beaver Creek thrust. About 300 yards west of the junction of the shift zone and the Baldy Pass thrust, the thrust fault passes into an overturned anticline. Since there was considerable differential movement in the hanging-wall block of this thrust and none in the foot-wall block, the former was the active block. It is obvious that the displacement of an active block increases laterally from the end of a thrust toward its central portion. Thus, since a large part of the differential movement in the active block of the Baldy Pass thrust near its western end occurred on the Baldy Pass shift zone, the eastern side of this zone must have been displaced southward with respect to the western. The swing in the outcrop pattern of every formation in crossing the zone is such that the outcrops of the formations west of the zone appear to have been shifted southward relative to those east of it. This difference in direction between the stratigraphic shift and the actual shift is to be expected, for the Baldy Pass thrust is a high-angle fault, whereas beds in the hanging wall of the thrust, excluding those in the shift zone, have an aveage dip of about 35° NE.

Davison Creek shift zone.—Lying about $\frac{3}{4}$ mile west of the Baldy Pass shift zone and striking N. 30° E. is the Davison Creek shift zone, the western side of which has been displaced southward. In this case the stratigraphic shift and the actual shift are in the same direction. The Davison Creek shift zone was produced by differential movement on the Suce Creek thrust fault, the part of the thrust sheet west of the zone having been overthrust farther to the south than the part east of it. The resulting difference in displacement and in crustal shortening, on either side of the zone, is equalized north of the Dry Creek thrust fault on the northern limb of the Dry Creek Ridge anticline. North of the junction of the shift zone and the thrust there is a broad poorly defined shift zone in the anticline, whose western side has also been displaced southward. The difference in crustal shortening on the two sides of this zone, which was without doubt continuous with the Davison Creek shift zone prior to faulting on the Dry Creek thrust, is equalized to the north by the change in the dip of the northern limb of the anticline along its strike.

Stumbo Mountain shift zone.—The stratigraphic and actual shift on this zone are similar to those on the Davison Creek shift zone.

The difference in crustal shortening on the two sides of the Stumbo Mountain shift zone is also equalized north of the Dry Creek thrust fault. The Dry Creek Ridge tear fault is located a short distance west of the junction of the shift zone and the thrust. The section of the Dry Creek Ridge anticline east of the tear was more compressed than the section west of it. This difference in crustal shortening on the two sides of the tear is the opposite of that on the two sides of the shift zone and compensates it.

CHRONOLOGICAL SEQUENCE OF THE STRUCTURES IN THE AREA

GENERAL

The structures in the Livingston Peak area were developed during two distinct stages of the Laramide revolution which were separated by a considerable interval of time. The structures produced during the early stage were formed by deep-seated stresses, whereas those developed in the later stage were formed by stresses acting at no great depth. The later stage may itself be divided into two substages, during each of which a group of essentially contemporaneous structures developed. It should be noted, however, that the chronological sequence to be described is based entirely upon structural evidence, for no Tertiary or late Upper Cretaceous strata, by means of which the orogenic movements might be dated, occur within the area.

STRUCTURES DEVELOPED IN THE EARLY STAGE

In this stage the North Snowy block of the Beartooth Mountains was strongly upthrust and tilted to the northeast. Most of the displacement along the western side of the block occurred on the Deep Creek Ridge normal fault which, during the early stage, passed northward without a break into the Plateau monocline. The remainder of the displacement occurred on the smaller Deep Creek Ridge monocline.

STRUCTURES DEVELOPED IN THE LATER STAGE

During the first substage of deformation the Suce Creek–Window overthrust fault was formed by comparatively shallow compressive stresses. This overthrust fault is known to have been developed after the upthrusting of the North Snowy block, for it has displaced the Deep Creek Ridge fault, along which the block was tilted.

When the thrust sheet advanced southward, its eastern section encountered the western extremity of the Beartooth Range and, after riding a short distance up the dip slope of the North Snowy block, was stopped by the obstruction. Further compression caused the western section, whose forward movement was relatively unobstructed, to be sheared from the remainder of the overthrust mass along the South Dry Creek tear fault, and the Stumbo Mountain and Davison Creek shift zones. There being no buttress to resist its southward advance, this section continued to move forward over the region of low structural relief west of the range until it was finally stopped by friction. Meanwhile the eastern section of the thrust sheet buckled, when subjected to further compression, giving rise to the development of the Dry Creek Ridge anticline, the Dry Creek syncline, the Baldy Pass thrust fault, and the Baldy Pass shift zone north of the Beartooth buttress.

After the Suce Creek–Window thrust sheet had been torn by horizontal shearing stresses, it was divided into four blocks by the South Dry Creek tear, and the Stumbo Mountain and Davison Creek shift zones. The southward displacement of each of these blocks is greater than that of the adjoining block east of it and less than that of the block west of it. This westward increase in the amount of displacement is largely equalized to the north by the eastward increase in the amount of compression of the complex Dry Creek Ridge anticline. Hence the folding of this anticline, and of the associated Dry Creek syncline, must have occurred simultaneously with the tearing of the major thrust sheet.

The Baldy Pass shift zone differs from the other shift zones in having the direction of shift reversed and in not extending to the trace of the Suce Creek thrust fault. Despite these differences, it is believed to have been formed at about the same time as the others for the following reasons. The Dry Creek thrust fault has displaced the northern end of the Davison Creek shift zone and the structural continuation of the Stumbo Mountain shift zone—the Dry Creek Ridge tear fault. The Beaver Creek thrust fault, which is the structural continuation of the Dry Creek thrust, has cut off the northern end of the Baldy Pass shift zone. From these relationships it can be seen that the three shift zones must have been formed at about

the same time, for they all preceded the thrusting which produced the thrust faults mentioned. Since the Baldy Pass shift zone was formed by the differential forward movement of the Baldy Pass thrust sheet, the Baldy Pass thrust fault must also be essentially contemporaneous with it.

In the foot-wall block of the Suce Creek–Window overthrust there are several structures which were formed by the unbalanced stresses involved in the southward advance of the thrust sheet and are therefore contemporaneous with the overthrusting. East of the Yellowstone Valley the open folds on the dip slope of the North Snowy block were produced in this way. West of the Yellowstone Valley the Strickland Creek thrust fault was developed, and the Trail Creek anticline was folded and, in places, overturned and thrust-faulted.

The first substage of the later stage of deformation ended when the Suce Creek–Window thrust sheet ceased to move southward, its eastern section having been stopped by the Beartooth buttress and its western section having been stopped by friction. Renewed compression caused the development of another group of structures north of the trace of this thrust fault, the formation of which occurred in the second substage. Although it is possible that these two substages may overlap somewhat, it can be proved that the structures of the first were at least close to completion before those of the second were initiated.

The Canyon Mountain thrust fault resulted from the buckling of the westernmost part of the Suce Creek–Window thrust sheet after this part had been stopped by friction. Since this part of the thrust sheet was the last to stop, this structure must have been formed after the first substage had ended. South of the trace of the Canyon Mountain thrust fault one may observe a upwarp and a downwarp of the fault plane of the major thrust. It is obvious that this warping also must have occurred after the first substage had closed.

Evidence has already been presented to show that the thrusting which produced the Dry Creek and Beaver Creek thrust faults occurred after the completion of the three shift zones. Since these shift zones were active throughout the greater part of the first substage, this thrusting must have taken place in the second substage.

OVERTHRUSTING VERSUS UNDERTHRUSTING

An overthrust is by definition a thrust fault whose hanging wall has moved up the dip of the fault plane during thrusting. Conversely an underthrust is a thrust fault whose foot wall has moved down the dip of the fault plane during thrusting. It is possible, though perhaps less likely, that a combination of these movements may occur, in which case the fault cannot be classified as either an overthrust or an underthrust but must be designated simply as a thrust.

The displacement on a thrust fault increases laterally along its strike from none at its ends toward the central part of the structure. Thus the central section of at least one of the blocks must have moved a greater distance over or under the other block than has either of its end sections. During the differential forward advance of this block horizontal shearing stresses would be set up within it parallel to its direction of movement. In cases where these have caused tear faults or shift zones, such structures may be used to determine whether the hanging wall or the foot wall of the thrust fault was the active block during thrusting.

A tear fault, which is limited to one block of a thrust fault, is safely interpreted in only two ways. It must have been formed either at the time of thrust faulting or before thrust faulting was initiated. If the tear was formed at the time of thrust faulting, the block in which it is located must have been the active block of the thrust fault, for the existence of the tear fault proves differential advance and active slip within this block. Since it is rather unlikely that a thrust fault would displace an earlier tear in such a way that later only one end of the tear fault would be observed at the surface, it seems safe to state that a tear fault (or shift zone) limited to the upper block of a thrust fault is probably indicative of overthrusting, whereas one limited to the lower block is probably indicative of underthrusting. This criterion was suggested and first used by Charles W. Wilson, Jr., in his report on the thrust fault near Gardiner, Montana.[1]

Suce Creek–Window thrust fault.—There are two shift zones and one tear fault limited to the hanging-wall block of the Suce Creek–

[1] "Geology of the Thrust Fault near Gardiner, Montana," *Jour. Geol.*, Vol. XLII (1934), p. 656.

Window thrust fault. If these structures had been produced before thrust faulting was initiated, one would naturally expect to find similar structures in the foot-wall block of the thrust. No tear structures have been observed, however, for many miles south of the trace of the thrust fault. Hence this fault is probably an overthrust.

The strike of the Suce Creek–Window thrust fault near the eastern boundary of the Livingston Peak area is N. 70° W., whereas at the western boundary it is N. 80° E. This change in strike takes place gradually. The strikes of the three tear structures in the overriding block of the thrust fault are, from east to west, N. 30° E., N. 25° E., and north-south. Thus each of the tear structures joins the thrust fault at an angle closely approximating 90°. If the tear structures were formed by shearing stresses set up in an overthrust sheet parallel to its movement, they would ideally join the thrust fault at an angle of 90°.

The three tear structures in the Suce Creek–Window thrust sheet radiate from a relatively small area within the northwestern corner of the North Snowy block. If the thrust fault is assumed to be an overthrust, this unusual radial pattern can easily be explained. An overthrust sheet which encountered a buttress, such as the North Snowy block is known to have constituted, would tend to pivot around this buttress. Tearing of the overthrust sheet would result from the differential resistance offered by the buttress to its forward advance. The net result of this pivoting and tearing would be that, after compression had ceased, the tear faults and shift zones in the overthrust sheet would radiate from the corner of the buttress.

It seems utterly impossible that these intimate relationships between the three tear structures in the Suce Creek–Window thrust sheet and the Suce Creek–Window thrust fault would exist if the tear structures had been formed before thrust faulting was initiated. Therefore it seems safe to conclude that the Suce Creek–Window thrust fault is an overthrust.

During part of the summer of 1935, C. W. Wilson, Jr., mapped the eastern end of this thrust fault where it passes into an overturned fold near the West Boulder River. After applying the criterion proposed by T. S. Lovering on the swing of the strike of the

strata associated with the passage of a thrust fault into a fold, he too concluded that the fault was an overthrust.[2]

Baldy Pass thrust fault.—The Baldy Pass shift zone, which is limited to the hanging-wall block of the Baldy Pass thrust fault, joins the thrust at an angle of about 75°. There are no shift zones or tear faults south of the trace of the thrust. Hence this fault is probably an overthrust.

Dry Creek and Beaver Creek thrust faults.—Near its passage into the Dry Creek syncline the Dry Creek thrust fault has displaced the Davison Creek shift zone. The displaced sections of this zone are similar in that on both of them the amount of shift decreases toward the north. The amount of shift on the northern section, however, is much greater than that on the southern section. This discrepancy can be explained only if it is assumed that movement on the northern section was renewed during the development of the Dry Creek thrust fault. As the northern section of this zone lies in the hanging-wall block of the Dry Creek thrust fault, this fault must be an overthrust. The Dry Creek and Beaver thrust faults are parts of the same structural lineament and have similar dips and strikes. Therefore the Beaver Creek thrust must also be an overthrust.

Canyon Mountain and Strickland Creek thrust faults.—As no shift zones or tear faults have been observed in the western part of the Livingston Peak area, where these faults are located, and as neither of these faults can actually be traced laterally into an overturned fold, they cannot be definitely classified as either overthrusts or underthrusts. Each of them, however, resembles in many respects one or more of the thrust faults already discussed. Therefore it is believed that they likewise are probably overthrusts.

MECHANICS OF DEFORMATION

THE UPLIFT OF THE NORTH SNOWY BLOCK

The stresses involved.—If, when deep-seated lateral compression takes place, there are zones of weakness in the earth's outer crust, the mass subjected to compression will tend to elongate vertically

[2] C. W. Wilson, Jr., personal communication; T. S. Lovering, "Field Evidence To Distinguish Overthrusting from Underthrusting," *Jour. Geol.*, Vol. XL (1932), pp. 651–63.

in these zones, lifting a portion of the outer crust against gravity. Since the North Snowy block of the Beartooth Range is bounded on two sides by nearly vertical faults, it seems likely that it was uplifted in this way.

Pre-existing zones of weakness.—The North Snowy block is bounded on its western side by a high-angle fault, which strikes N. 25° E., and on its southern side by a zone of steeply inclined faults, which trends about east and west. These directions have more than local significance, for it has been observed that

> throughout the [Beartooth-Bighorn] region the axes of the major uplifts and of anticlines, of flexures, and of overthrust mountain borders tend to follow one of three directions which dominate the whole structural pattern. These are N. 25° W., about N. 20° E., and east-west.[3]

The simplicity of this pattern strongly suggests that the boundaries of the blocklike uplifts in the region were controlled by a pre-existing system of linear zones of weakness. Since there was little diastrophism in this region during the Paleozoic and Mesozoic eras, these linear zones of weakness must have been formed in the pre-Cambrian.

In 1933 Drs. Ernst and Hans Cloos studied the pre-Cambrian structure of the Beartooth, Bighorn, and Black Hills uplifts. They noted that "though differing individually in every detail, the three structural units seem to indicate coincidence between pre-Cambrian doming and their present boundaries."[4]

The pre-Cambrian structure of the western part of the Beartooth Range has not as yet been studied in detail. There is evidence, however, that the Deep Creek Ridge normal fault, which bounds the North Snowy block on its western side, coincides with a pre-Cambrian zone of weakness.

Between Mill Creek and the northwestern corner of Yellowstone National Park is a striking alinement of hot springs and large extinct volcanoes. This alinement, which trends between N. 20° E. and N. 25° E., includes Chico and Corwin hot springs, the basic sills in

[3] W. H. Bucher, W. T. Thom, Jr., and R. T. Chamberlin, "Geologic Problems of the Beartooth-Bighorn Region," *Geol. Soc. Amer. Bull. 45* (1934), p. 175.

[4] "Pre-Cambrian Structures in the Beartooth, Bighorn, and Black Hills Uplifts, and Its Coincidence with Tertiary Uplifting," *Geol. Soc. Amer. Proc. for 1934*, p. 56.

Cinnabar Mountain, and Electric and Emigrant peaks, which are erosional remnants of extinct volcanoes. This alinement of magmatic and hot-water conduits crosses the pre-Cambrian core of the South Snowy block. Since there is no Laramide faulting in this section of the South Snowy block, the alinement must have been controlled by a linear zone of weakness in the pre-Cambrian rocks. If this zone of weakness were projected to the north-northeast of Mill Creek, it would parallel the western face of the North Snowy block and would lie about a mile west of the mountain front. It has already been shown that, if the southern end of the Deep Creek Ridge normal fault were projected south-southwest of Deep Creek, it would parallel the mountain front and would lie about a mile west of it. Therefore it is believed that the same zone of weakness determined the position of both the normal fault and the series of hot springs and extinct volcanoes. Substantiating this belief is the fact that the only hot-spring deposit in the Livingston Peak area is located on the eastern side of the Lower Canyon of the Yellowstone River at the northern end of the Plateau monocline, which is the northern structural continuation of the Deep Creek Ridge normal fault.

There are no known hot springs or large extinct volcanoes for many miles west of this zone of weakness as defined above. There are, however, two groups of intrusives east of it, which are located in the Mill Creek basin and along the northern front of the range. The writer believes that these groups are probably in some way related to other zones of weakness, one of which determined the position of the fault zone on the southern side of the North Snowy block.

Thus, before deep-seated compression took place, the segment of the earth's crust which now forms the North Snowy block of the Beartooth Range was probably partially outlined on at least three sides by zones of weakness. For this reason, when deep-seated compression did occur, this segment offered relatively little resistance to upthrusting. Since it is very improbable that a block would ever be uniformly uplifted by upthrusting, the fact that the North Snowy block is at present tilted to the northeast needs no further explanation.

INITIATION OF THE SUCE CREEK–WINDOW THRUST FAULT

Preceding structure.—It is known that the western part of the Suce Creek–Window thrust fault was developed from an overturned anticline, for it has been traced laterally into this type of structure near the West Boulder River. This anticline must have been located near the base of the North Snowy block, because the Plateau monocline, along which the block was uplifted, terminates a short distance north of the present trace of the thrust fault.

The origin of this anticline is easily explained. When a segment of the earth's crust is bent upward by lateral compression, such minor folds as develop tend to have the same symmetry, or asymmetry, as the major uplift, like drag folds on the limbs of ordinary anticlines. If the anticline which preceded the Suce Creek–Window thrust fault was formed in this way, one would expect to find similar folds to the east of it. East of the West Boulder River there is a large anticline which parallels the mountain front. This anticline has also been deformed by a plainsward-dipping thrust fault of large displacement.

Stresses involved in the formation of the thrust fault.—At the beginning of the later stage of the Laramide revolution the upper surface of the pre-Cambrian of the North Snowy block sloped at a low angle toward the northeast. Near the base of the block this surface was folded into an anticline whose southwestern flank was much steeper than its northeastern flank. West of the North Snowy block, however, the upper surface of the pre-Cambrian was essentially flat.

When the region was subjected to shallow compressive stresses, these stresses were influenced by the structures just described and two stress couples were set up. The greater of these tended to push the North Snowy block north-northeastward over the region of low structural relief north of the range. The lesser tended to push the anticline at the base of the block toward the south-southwest. Owing to the difference in size between the anticline and the uplifted block, the anticline was more easily deformed. The initial asymmetry of the anticline caused the thrust fault, which was developed, to dip toward the north-northeast. The angle of dip of the thrust fault, however, was controlled by the greater stress couple. This

couple rotated the shearing plane, along which the fault broke, toward the vertical. Consequently the dip of the eastern section of the thrust fault is considerably in excess of the 45° angle at which thrust faults should theoretically break. West of the North Snowy block, however, where only the lesser stress couple was active, the dip of the thrust fault is much lower.

DEFORMATION DURING THE DEVELOPMENT OF THE SUCE CREEK–WINDOW THRUST

Because of the lower dip of the western section of the Suce Creek–Window thrust fault, the western part of the overthrust sheet was more easily moved than the eastern part As a result there is at present a westward increase in the amount of displacement on the fault. This increase in displacement is equalized north of the trace of the thrust by the westward decrease in the amount of crustal shortening observed in the group of structures which developed in the overriding block of the thrust during the first substage of the later stage of deformation.

As there is a tendency for an advancing overthrust sheet to drag its foot wall along with it, one would expect to find the most deformation in the western section of the foot-wall block of the Suce Creek–Window thrust, because the greatest amount of displacement is observed on the western section of this fault. Such is the case, for a marked westward increase in the amount of crustal shortening is found in the group of structures located south of the trace of the major thrust fault. One effect of this increase is the change in the strike of the thrust fault from N. 70° W. on the southern slope of Baldy Ridge to N. 80° E. west of the Yellowstone River. Another effect is the radial pattern of the tear structures in the overthrust sheet.

DEFORMATION AFTER THE COMPLETION OF THE SUCE CREEK–WINDOW THRUST

At the end of the first substage of the later stage of deformation there existed a westward decrease in the amount of crustal shortening in the overthrust sheet of the Suce Creek–Window thrust fault. Hence, when lateral compression was renewed, the western part of the thrust sheet offered less resistance to further deformation than

did the eastern part. As a result it was more deformed, and a westward increase in the amount of crustal shortening in the series of structures produced in the closing substage of the orogeny is now observed.

THE BEARTOOTH BUTTRESS

The Beartooth buttress resembles in many respects the better-known Adirondack buttress, which controlled the trends and grouping of the thrust faults and folds in the northern Appalachians, and the well-known Black Forest buttress, around which were deflected the folds of the Jura Mountains. All three of these buttresses are structural uplifts formed by deep-seated stresses, and are larger and older than the folded and faulted structures adjacent to them.

It has been shown that the North Snowy block of the Beartooth Mountains acted as a buttress in the later stage of the Laramide orogeny largely because of its high structural elevation and relatively great size. Inherent rigidity of the rocks, which is so frequently referred to in the descriptions of other buttresses, could have played but a small part in the buttress action of this block, for crystalline rocks are found not only in the buttress but also in the overthrust sheet, whose forward advance the buttress obstructed.

PRESSURE-BOX EXPERIMENTS

During the spring of 1935 the writer performed several pressure-box experiments in the structural laboratory of the University of Chicago, the purpose of which was to find out what might happen when an advancing overthrust sheet encounters a buttress like that in the Livingston Peak area. Professor R. T. Chamberlin supervised the experiments and aided the writer in their interpretation.

Apparatus.—The pressure box in which the experiments were carried out has a square base, measuring 19 inches on a side, and is 4 inches deep. The pressure was applied by means of a push block propelled by a powerful jackscrew. Since the push block was not attached to the screw, it was free to pivot when differential resistance to its forward movement was encountered. When the resistance was equal, however, the push block did not pivot, since the screw was in contact with the central part of the block. Damp sand

was used in the experiments, because it is easily molded and has a uniform composition.

Setup for the experiments.—The same experiment was repeated fourteen times. In order to facilitate a description of it and to give the proper orientation, the movable side of the pressure box will be called the "northern side." A mound of sand, 4 inches high, was built in the southeast corner of the box. The larger part of the surface of this mound sloped to the north at an angle of about 20°, simulating the Beartooth buttress. Near the western edge of the mound the surface sloped at an angle of about 80° to the west like the North Snowy block. In the northern half of the box an east-west asymmetrical anticline was built, whose crest had a height of about 1½ inches. This represented the anticline which preceded the Suce Creek–Window thrust fault. The steeper limb of this anticline faced south. The remainder of the box was filled with sand to a depth of 1 inch. Before pressure was applied, the damp sand was compacted by patting it with the palm of the hand.

Results.—When pressure was initiated, the low anticline was broken in every case by a northward-dipping overthrust fault. Upon the application of further pressure the overthrust sheet advanced southward, its eastern section riding up the dip slope of the mound in the southeastern corner of the pressure box. Near the western edge of the mound the thrust sheet was generally broken by several small tear faults. In the five out of the fourteen experiments in which these faults were well developed, it was observed that the upper surface of the eastern section of the thrust sheet was no longer a plane surface but had been slightly warped.

When still further pressure was applied, the push block pivoted, its western end moving forward more rapidly. Coincident with the pivoting of the push block a number of small northward-dipping overthrust faults developed in the southwestern corner of the pressure box south of the trace of the major thrust.

Conclusion.—When these experiments were undertaken, it was fully realized that the results obtained would be suggestive rather than conclusive. The structural pattern produced in the pressure box, however, was so strikingly similar, even in its details, to that

observed in the Livingston Peak area that the writer feels justified in stressing the importance of the Beartooth buttress in the orogenic history of the Livingston Peak area.

ACKNOWLEDGMENTS.—The writer wishes to express his gratitude to Drs. Rollin T. Chamberlin, William T. Thom, Jr., and Walter H. Bucher for their valuable suggestions and assistance during the field work. The writer is also especially indebted to Dr. Chamberlin for criticizing the entire manuscript and for supervising the pressure-box experiments. Dr. Charles W. Wilson, Jr., kindly read and criticized the section of the manuscript dealing with overthrusting and underthrusting.

The writer wishes to thank Dr. Donald J. MacNeil and Dr. Dorr Skeels for permission to use a portion of an unpublished map, which they helped prepare. During the summer of 1933, Dr. MacNeil, Dr. Skeels, and the writer were assisted in the field by Dr. John Lucke, Mr. Edward Whaley, and Mr. Rutledge Howard. Mr. Charles MacClintock ably assisted the writer during the field seasons of 1934 and 1935. The photographs were selected from a group taken by Mr. McClintock and Mrs. Lammers. The drafting was done by Mr. Franklin Wray and Robert Basile.

FOLDING OF THE CALIFORNIA COAST RANGE TYPE ILLUSTRATED BY A SERIES OF EXPERIMENTS[1]

BRUCE L. CLARK
University of California

ABSTRACT

The writer, in previous papers, has expressed the belief that a large portion of the folding in the Coast Range of California is the result of drag on faults produced at times of compression. This paper describes a number of experiments with plasteline where folding has been produced as the result of drag. It is believed that these experiments illustrate and duplicate the conditions under which folding has taken place along the faults in the Coast Ranges and in other parts of the world.

The latter part of the paper gives a number of illustrations of Coast Range folding which is associated with faulting; the character of the folding is believed to have been the result of drag combined with compression. It is the writer's belief that this type of folding is fairly common all over the world.

INTRODUCTION

The California Coast Range type of folding is here defined as major folding which was produced as the result of drag combined with compression. The drag was brought about by the horizontal and vertical components of the forces resulting from the movements of the blocks on either one or both sides of a fault. The concept of folding as the result of drag along a fault is not a new one, but usually it has been considered as only a minor phenomenon which is confined to the immediate vicinity of the fault.

Most geologists hold that folding is due to direct tangential compression, and nearly all the published experiments pertaining to folding illustrate this by a plunger pushed directly against the mass to be folded. As a result, invariably an anticlinal fold was formed next to the plunger block. So far as the writer knows, the experiments described in this paper are the first where folding has been produced by compression combined with horizontal and vertical movements on a plane corresponding to a fault.

The majority of West Coast geologists in the past have maintained, and some still hold, that folding was the principal factor in the early deformation of the California Coast Ranges, that the major basins of deposition were produced by folding and down-

[1] A contribution from the Museum of Paleontology, University of California.

warping, and that the major folding took place before the faulting. It was recognized that a few of the faults, like the San Andreas, probably antedated the Miocene epoch. R. D. Reed[2] in a recent book maintains the thesis that, in general, folding preceded the faulting. A considerable number of other West Coast geologists, including the writer, hold that the primary faulting is the most fundamental structure in the Coast Ranges and that folding is secondary to the faulting.

The idea of folding, as illustrated by the experiments described in this paper, was first developed as a result of field studies. Over and over again the writer was faced with the problem of how certain deposits could possibly have been brought to their present position by the commonly recognized methods and, in case after case, he was forced to the conclusion that some other explanation was necessary. The drag theory was accepted only after all the other possibilities had been eliminated. The evidence which supports this concept is integral with that for the old age of the faulting and for fault-trough deposition. This has been discussed in a number of other papers,[3] and it is not necessary to review the details here.

A concept somewhat similar to the one discussed in this paper is that of F. P. Vickery,[4] who believes that folding in the California Coast Ranges has been chiefly the result of compression of one block against another, and that while the blocks were being compressed there were at the same time rotational forces which produced the folding oblique to the faults, the direction of the folding depending upon the direction of the forces. Vickery emphasizes the importance of horizontal movements on the faults and applies the principle first outlined by W. J. Mead[5] in his experiment in which plastic mate-

[2] "Geology of California," *Amer. Petrol. Geol.* (1933), pp. 1–354.

[3] Bruce L. Clark, "Tectonics of the Valle Grande of California," *Amer. Assoc. Petrol. Geol. Bull. 13*, No. 3 (1929), pp. 199–238; "Tectonics of the Coast Ranges of the Middle California," *Geol. Soc. Amer. Bull. 41* (1930), pp. 747–828, Pls. XIV–XXII (11 figs.); "Age of the Primary Faults in the Coast Ranges of California," *Jour. Geol.*, Vol. XL, No. 5 (1932), pp. 384–401; "Tectonics of Mount Diablo and Coalinga Areas, Middle Coast Ranges of California," *Geol. Soc. Amer. Bull. 46* (1935), pp. 1025–78.

[4] "Structural Dynamics of the Livermore Region," *Jour. Geol.*, Vol. XXXIII, No. 6 (1925), pp. 608–28.

[5] "Notes on the Mechanics of Geologic Structures," *Jour. Geol.*, Vol. XXVIII (1920).

rial was folded as the result of horizontal rotational stress. The writer does not doubt the importance of this principle; however, it does not take into account the vertical forces known to have existed on all these faults, which forces have dragged beds out of a graben along the bounding faults. These vertical forces, combined with the horizontal, also produced closures on folds which would not have been formed without them.

To summarize, some of the principal types of folding in the California Coast Ranges that are considered by the writer to be the result of drag combined with compression are:

1. Synclinal folds bounded by faults with no corresponding anticlines on either side. These isolated synclines are commonly found between blocks of competent rocks that are older than the deposits of the syncline, and the blocks show no evidence of folding but do give evidence of having been upthrust. Often the deposits on the outer margins of these synclines have been overturned against the bounding faults.

2. Deposits dipping monoclinally away from a fault toward a basin area in which the beds are flat or nearly so. Here again on the other side of the fault are older rocks showing no anticline along which the dipping sediments on the opposite side could have been raised. Very often these sediments bordering the fault, like those in the synclines, stand vertically or are overturned.

In both cases cited above, according to the writer's interpretation, the exposed dipping sediments of the synclinal or monoclinal areas bordering the bounding faults were originally deposited horizontally against the fault scarps. Often it can be shown that the sediments were derived from rocks immediately adjacent on the other side of the fault; thus, on the one side was a sinking area, on the other, a rising area. Compression and drag at the time of the Coast Range revolution raised the deeply buried beds to the surface. Figure 1 illustrates these types of folding.[6]

3. A third type of drag folding that is characteristic of the California Coast Ranges is a series of folds en echelon bordering a fault

[6] The writer appreciates the fact that in nature one would not expect to find an uneroded fault scarp, such as is illustrated in Fig. 1, under the conditions which are described in this paper. However, for purposes of theoretical discussion it seems best not to enter into the complications that would be brought about as a result of the erosion of the fault scarp.

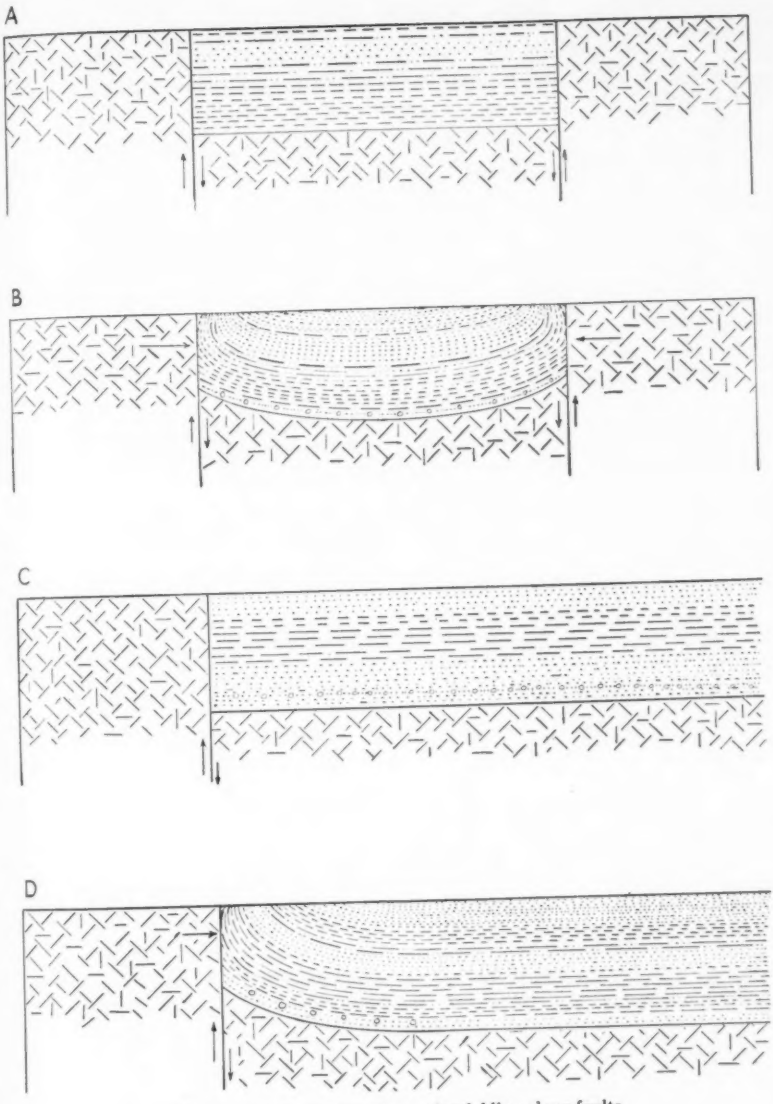


FIG. 1.—Cross sections illustrating folding along faults

zone. Almost invariably these are best developed next to the fault and fade out away from it. Folding of this type is observed along a large number of the major faults in middle and southern California. It is so typically associated with primary faulting that where such a series of folds is found with no related fault on the surface they, too, presumably were formed along a fault which is buried under the later sediments. In the majority of cases the echelon folds in the Coast Ranges begin at a primary fault and are confined to one side of it and, in a large proportion of cases, the deposits plunge away from the fault and, toward the middle of the block become flat-lying beds. The writer has expressed the opinion in his paper on "Tectonics of the Coast Ranges of Middle California"[7] that echelon folding of this type is the result of drag produced by vertical and horizontal movements at the time of compression. In this type the beds were dragged up obliquely instead of directly, as was the case in the areas of the isolated synclines and monoclines previously mentioned. This oblique movement was the result of the addition of the horizontal component to the vertical, as illustrated in an experiment described later in this paper.

EXPERIMENTS IN FOLDING OF SMALL PLASTELINE BLOCKS

During May, 1932, a series of experiments with small plasteline blocks was undertaken in order to test some of the writer's conclusions on folding by drag. Assistance and helpful suggestions were given by Lawrence Woodworth, Earl Turner, and William Effinger.

Figure 2 shows a front view of the apparatus used in the first three experiments; it consists of a block of plasteline about 10 inches square, which lies on a board, with one of the longer margins of the plasteline extending a little beyond the edge of the board; the plasteline was compressed by another board on which plasteline had been smeared to give it a rough surface. The use of small plasteline blocks was suggested by the description of experiments by H. Cloos.[8]

EXPERIMENT I. FOLDING PRODUCED BY VERTICAL UPLIFT AT TIME OF COMPRESSION

In the first experiment, which was very simple, a horizontal block of plasteline, composed of several layers about $\frac{3}{4}$ inch thick,

[7] *Loc cit.*, pp. 823–28.

[8] "Zur experimentellen Tektonik, Brüche und Falten," *Naturwissensch.*, Vol. XIX (1931), pp. 242–47 (10 figs.).

was used. The compression board was pressed against the overhanging edge of the plasteline and at the same time was raised. As a result, the horizontal plasteline layers were turned upward (Fig. 3). We have here what corresponds to the raising of beds on the border of a graben from horizontal toward vertical position. If the compression were continued sufficiently, the beds would be brought to verticality and finally overturned.

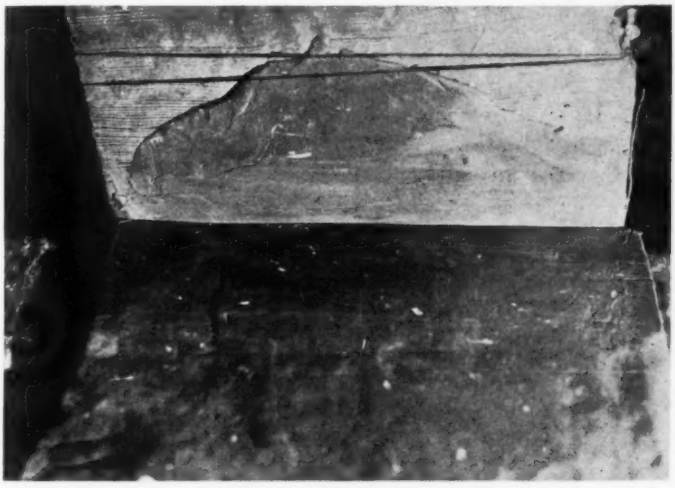


FIG. 2.—Apparatus used in Experiments I–III

When the block was subjected to direct compression only, an anticlinal fold was formed along its margin. The only way in which the beds could be made to dip continuously away from the compression block under the conditions of this experiment was by raising the compression board and at the same time pressing it against the plasteline.

EXPERIMENT II. FOLDING PRODUCED WITH COMPRESSION BOARD RISING ON PLANE INCLINED 5°–10°

The second experiment was to compress the horizontal block of plasteline, while at the same time the compression board was slid horizontally along an inclined plane. Such compression has both horizontal and vertical components. Figure 4 shows the result of this experiment when the compression block was moved along an in-

clined plane of 5.° The thickness of the plasteline block was a little over $\frac{1}{4}$ inch. In this case three folds were formed with a maximum

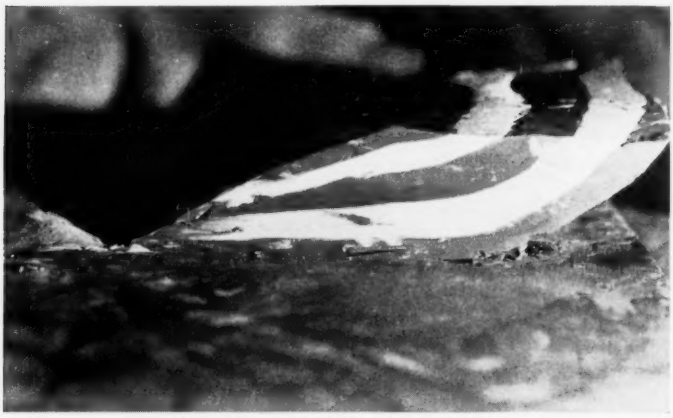


FIG. 3.—Results of Experiment I. Compression board removed from the right

FIG. 4.—Results of Experiment II

height of a little over $\frac{1}{2}$ inch. The longest of the three folds was close to 5 inches in length. Figure 5 is another example of this experiment

under the same conditions. In this case there were two folds, the axis of the larger one making a much smaller angle with the side of the compression block than that of the smaller fold on the right. The length of the larger fold was about $5\frac{1}{2}$ inches.

Figure 6 shows still another of these trials. Here it will be noted that there are three folds. The large middle fold shows a decided closure. The other two folds open up against the compression board.

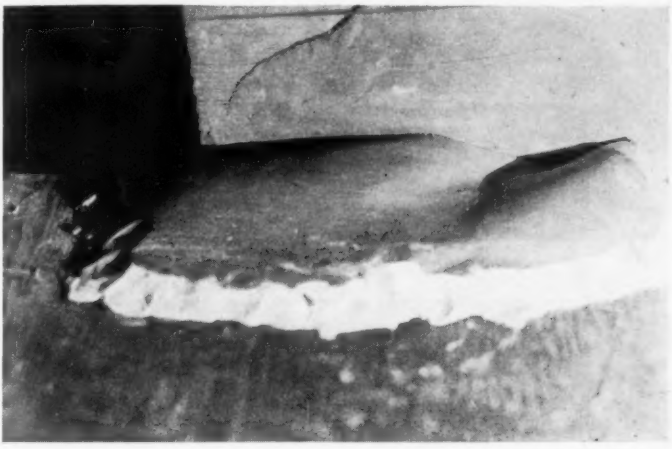


FIG. 5.—Results of Experiment II

This experiment with the compression board on an inclined plane of 5° was repeated many times. In some cases three folds were formed, though the number of folds was naturally limited by the small size of the block. In the two examples just given the folds opened against the compression board without any closure. In some cases, however, the folds showed a slight closure next to the board.

Figure 7 is a good example of what happens when the vertical component is increased by causing the compression board to rise at an angle of 10°. Here the folds were much shorter and their plunge was much steeper. They all opened up against the compression block without any closure. The results of these experiments were what one would deduce from Experiment I: i.e., the greater the

FIG. 6.—Results of Experiment II

FIG. 7.—Results of Experiment II, with compression board rising at an angle of 10°

vertical component, the greater the direct uplift of the compressed beds along the hypothetical fault plane which is represented by the compression board.

Figure 8 shows the side view of the folded plasteline with the compression block removed after one of the trials of Experiment II.

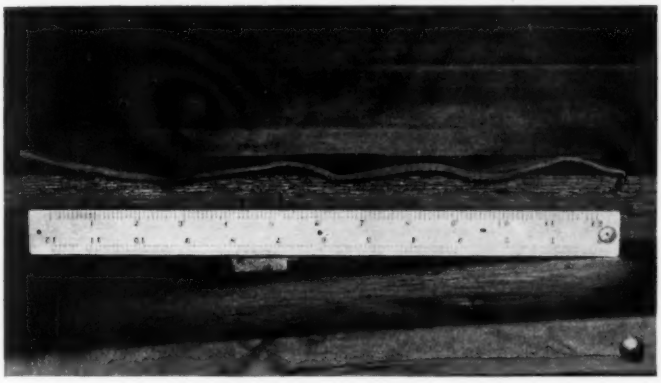


FIG. 8.—Side view of one of the results of Experiment II

EXPERIMENT III. THE COMPRESSION BLOCK MOVED HORIZONTALLY ONLY

In this case (Fig. 9) the compression block was not raised on an inclined plane as in Experiment II but was moved horizontally parallel to the line of the hypothetical fault. Three folds were developed. It will be noted that here the axial lines of the folds were horizontal, or nearly so, and that there was no closure; this was because there was no vertical movement of the compression block.

EXPERIMENT IV. PLASTELINE BLOCK FOLDED BY DIRECT COMPRESSION FIRST, AFTER WHICH A LONGTITUDINAL HORIZONTAL MOVEMENT WAS GIVEN TO THE BOARD

Figure 10 shows a block of plasteline which was folded first by compression at right angles to the hypothetical fault; the result was a simple anticlinal fold paralleling the edge of the block. However, when the pressure was continued and at the same time the compression block was moved horizontally at right angles to the direction of the earlier compression, a series of small domes was superimposed on the anticlinal folds.

FIG. 9.—Results of Experiment III

FIG. 10.—Results of Experiment IV

EXPERIMENT V. FOLDING PRODUCED BY COMPRESSING TWO PLASTELINE BLOCKS WITH A VERTICAL COMPONENT ADDED TO THE HORIZONTAL MOVEMENT

In the experiments just described only one block was compressed. The compression block was composed of competent material which did not fold or break, as might be the case in the earth if its counterpart were composed of crystalline or highly metamorphosed rocks. What would happen if the blocks on either side of a fault were composed of incompetent rocks—a condition which is more common than the other? In Experiment V two thin plasteline sheets, about $\frac{1}{4}$ inch thick, were placed on two boards with a fairly broad margin of the plasteline extending beyond the board on one side of each. These two free margins were brought together and compression was added to the joined sheets, while at the same time one of the blocks was moved on an inclined plane of about 1°, thus giving to the movement both a horizontal and a vertical component. In this experiment it was assumed that the fault had cut through to the surface before the folding took place.

Figure 11 shows one of the trials in this experiment. In this case a fold was formed on each block, the larger one being on the downthrown side. This fold was closed, with its axis nearly parallel to the line of division between the two blocks; the fold on the uplifted block was only slightly closed. It will be observed from the figure that there was a tendency for the two plasteline sheets to ride over each other. This was due to their thinness.

In another trial (Fig. 12) several broad, wavelike folds were formed on either side. Some of these were partially closed; others were open.

EXPERIMENT VI. FOLDING PRODUCED IN A BLOCK OF PLASTELINE PLACED ON TWO BOARDS SEPARATED BY A NARROW INTERSPACE

Geologists have long recognized that folding takes place along a buried fault. Experiment VI was undertaken to find out what would happen to the deposits above the fault when the blocks cut by the fault moved in a horizontal direction parallel to the line of the hypothetical fault. The two blocks across which the plasteline lies represent the deposits broken by the fault.

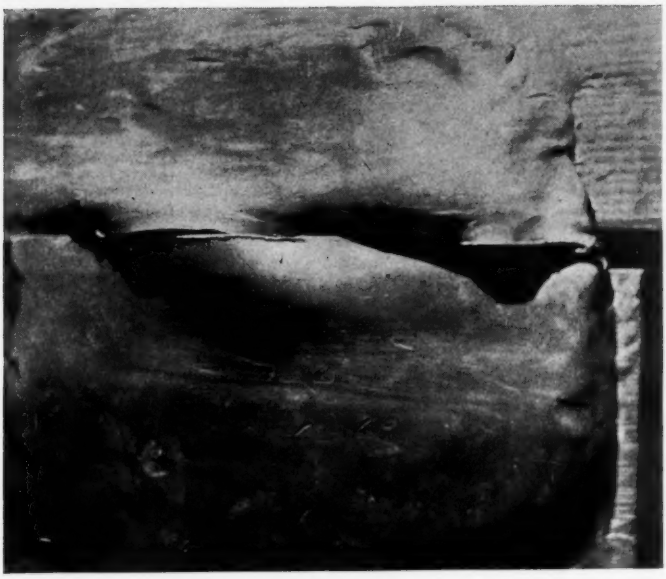


FIG. 11.—Results of Experiment V

FIG. 12.—Results of Experiment V

As will be seen from Figures 13 and 14, closed folds were formed on either side of the line between the two blocks. In every trial of this experiment a synclinal depression was formed at one end between the two blocks. This type of folding would be the result of torsion comparable with that produced by Mead[9] in his well-known experiment where plastic material was folded as the result of horizontal rotation. The writer expresses the opinion farther on in this paper that there is little evidence that this type of folding has been important along Inglewood fault in the Los Angeles basin area—an opinion not shared by several geologists.

EXPERIMENT VII. FOLDING PRODUCED BETWEEN TWO PLASTELINE BLOCKS, COMPRESSION ACCOMPANIED BY UPLIFT OF ONE BLOCK

In the seventh experiment two plasteline blocks about 2 inches thick were placed together and compressed, and at the same time one of them was raised vertically. The result of one of these trials is shown in Figure 15. The beds on the upthrown side have been dragged down, and those on the opposite side, up. However, it will be noted that there has been very little displacement along the hypothetical fault; i.e., the line separating the two blocks. In the other trials of this experiment, with thinner blocks of plasteline, the plasteline block on the upthrown side was dragged down to a vertical position and the one on the opposite side was dragged up to a vertical position.

In the writer's opinion the type of folding illustrated by Experiment VII is a rather common one in the Coast Ranges of California. In a recent paper the writer has described two such structures from the area south and southwest of Coalinga along the western border of the San Joaquin Valley; these had originally been mapped as unbroken anticlines. Later work showed that each of these so-called "anticlines" was broken along its axis by a fault along which there had been very little throw. The writer's explanation is that these apparent anticlines were produced as the result of drag along faults and that the folding originated in the same way as that illustrated by Experiment VII.

[9] Mead, *op. cit.*, pp. 505–23 (12 figs.).

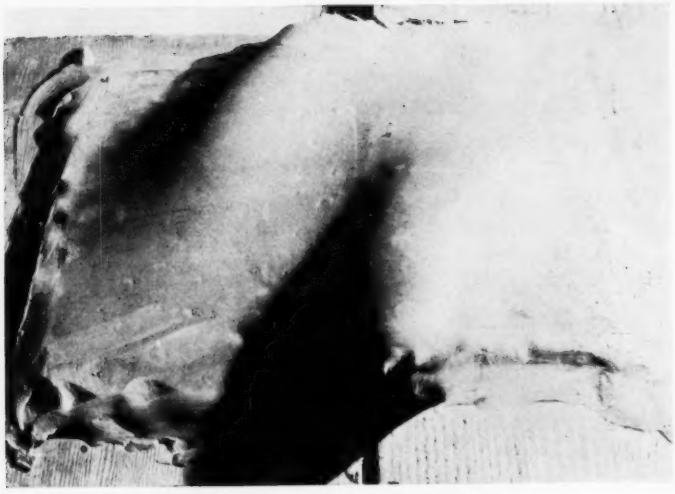


FIG. 13.—Results of Experiment VI

FIG. 14.—Results of Experiment VI

ILLUSTRATIONS OF FOLDING IN THE COAST RANGES

ISOLATED SYNCLINES AND MONOCLINES

In Experiment I the plasteline was folded up uniformly along the compression board, owing to the fact that the board was raised vertically while the compression was being applied. According to the writer's interpretation, it was this type of folding in the Coast Ranges that produced the isolated synclines bounded by faults and the monoclines which parallel a fault, already described in the introduction and illustrated in the diagrams of Figure 1. The beds which had originally been buried were brought to the surface as the result of drag. Some of the best examples of this isolated synclinal folding are found along the east side of the San Andreas fault zone to the west of the town of Coalinga. The geology of this area recently has been reviewed by the writer.[10] A number of other cases of this type of folding are shown in the cross sections given in the paper entitled "The Tectonics of the Coast Ranges of Middle California."[11]

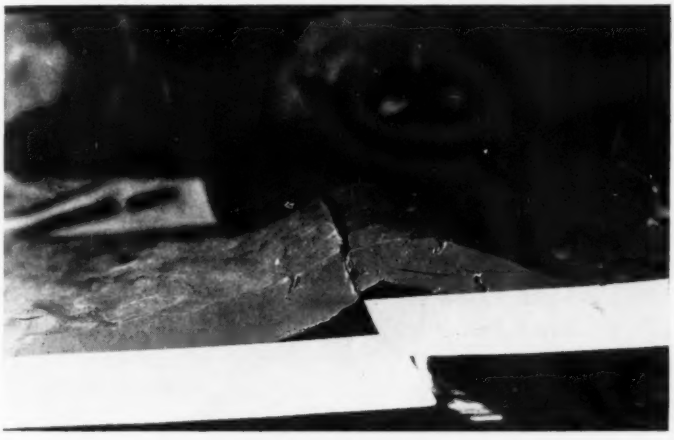


FIG. 15.—Results of Experiment VII

One of the best examples of monoclinal folding along a fault may

[10] Clark, "Tectonics of the Mount Diablo and Coalinga Areas, Middle Coast Ranges of California," *loc. cit.*, p. 1062; see Pl. LXXXIX for map and section.

[11] *Loc. cit.*, see sections on Pls. XVII, XVIII and XXI.

be seen on the east side of Mount Hamilton. Here steeply dipping, Cretaceous sediments are separated by a fault from the older Franciscan (Jurassic) rocks on the west. In the Cretaceous series lying immediately east of the fault is a great thickness of conglomerates[12] which were derived in a large part from the older Franciscan rocks on the west side. It was also noted that there is no anticlinal fold in the Franciscan rocks paralleling the fault on the west side, such as would be expected if this were a case of ordinary compressional folding. The section here corresponds very closely to the theoretical one shown in Figure 1*b*.

The writer[13] has also discussed in considerable detail the evidence for drag folding along the Riggs Canyon fault which cuts through the Mount Diablo quadrangle in the area to the south and west of Mount Diablo. Here on the west side of the fault is a great thickness of sediments, mostly of Tertiary age, which stand vertically and which in places are overturned; while on the east side there is no evidence of anticlinal folding such as would be necessary to bring these sediments to their present position according to the usual interpretation. Again, in this case there is good evidence to show that the faulting is deep seated and originated at an earlier date than most of the sediments through which it later broke, and that the Tertiary sediments were deposited in a fault trough, the northeastern boundary of which was the Riggs Canyon fault.

The folding along the Riggs Canyon fault has not been so simple as that of the isolated synclines or that of the monoclinal folding along the west side of the San Joaquin Valley to which reference has been made. For considerable distances along the fault, as, for example, the vicinity of Mount Diablo, the steeply dipping deposits run parallel to the fault. Here apparently the vertical components of the forces of drag were much stronger than the horizontal, the result being that the beds were brought to the surface as illustrated in Figure 1*b*. To the southwest of Mount Diablo is a series of faulted flexures and echelon folds along the fault, which foldings, according

[12] Clark, "Tectonics of the Mount Diablo and Coalinga Areas, Middle Coast Ranges of California," *loc. cit.*, pp. 1050–62.

[13] *Ibid.*, pp. 1075–78.

to the writer's interpretation, have been brought about by a combination of horizontal and vertical forces, as illustrated by Experiment II.

DRAG FOLDING IN THE LOS ANGELES BASIN

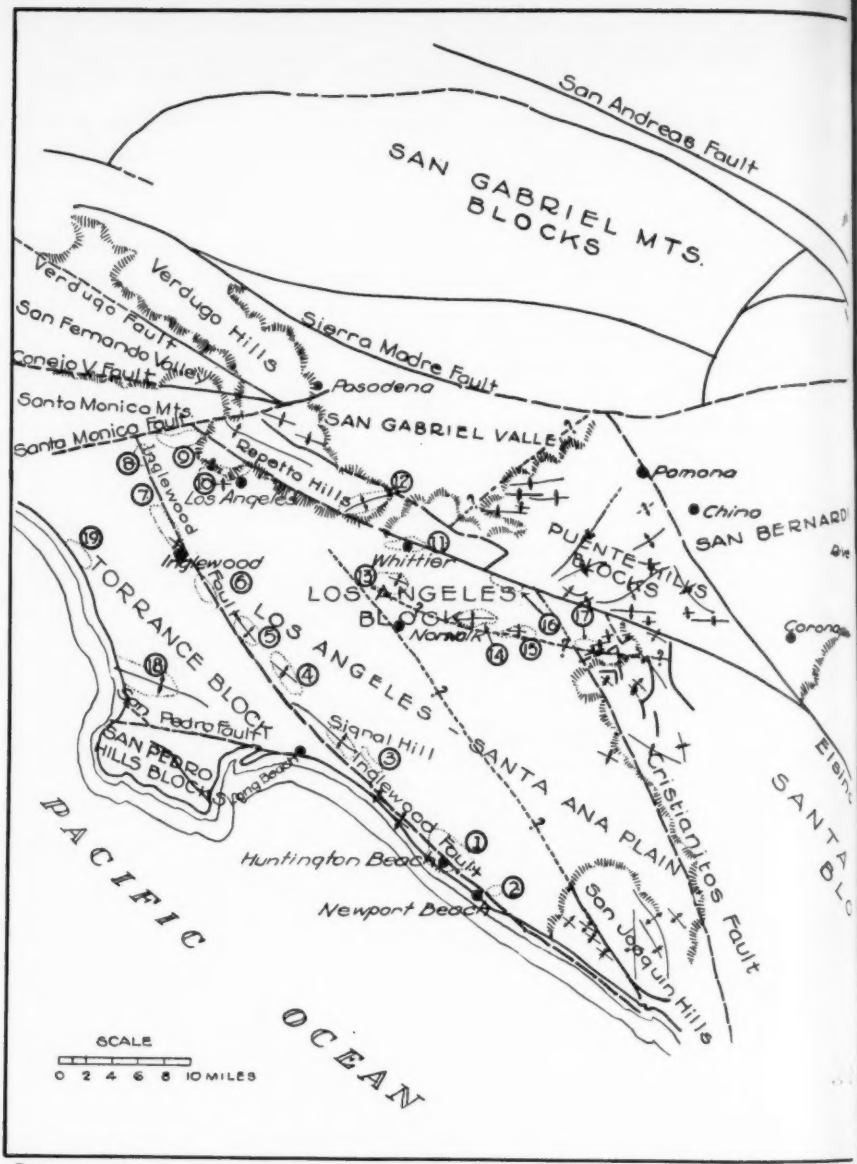
Southern California offers some excellent examples of folding by drag similar to the results obtained in the experiments. Figure 16 is a map showing the fault pattern and the location of the principal folds in the area generally referred to as the Los Angeles basin. The geology of the larger part of this area is described in a paper by W. A. English, entitled "Geology and Oil Resources of the Puente Hills Region, Southern California,"[14] to which the reader is referred for details.

As is shown in Figure 16, the Los Angeles basin is broken up into a number of fault blocks. The so-called "basin" area is bounded on the north by the San Gabriel Mountains which are formed of a series of blocks composed chiefly of old metamorphic and igneous rocks, in part of Paleozoic and in part of early Mesozoic age. These blocks have been raised on high-angle faults. It has been pointed out recently by Miller[15] that there is good evidence to show that the San Gabriel Mountain blocks were exposed to erosion during at least a large part of the Tertiary period, and in the writer's opinion there are good reasons for believing that this area was also exposed during the Cretaceous period. The basin area is bounded on the northwest side by the Santa Monica Mountains which have been raised as a block along a fault. The western and middle portions of this area are composed of Cretaceous and Tertiary sediments. Near the east end is a large mass of granite and older metamorphic rocks. The geology of the eastern portion of the Santa Monica Mountains has been recently described by Hoots.[16] Although the Santa Monica Mountain area is complicated by faulting, it has been raised as a unit on the south side along the Santa Monica fault and tilted toward the north.

[14] *U.S. Geol. Surv. Bull. 168* (1926), pp. 1–110 (14 pls., 3 figs.).

[15] W. J. Miller, "Geology of Western San Gabriel Mountains," *Univ. Calif. Publ. in Mathematics and Physical Sciences*, Vol. I, No. 1 (1934), pp. 74–82.

[16] H. Hoots, "Geology of the Eastern Part of the Santa Monica Mountains, Los Angeles County, California," *U.S. Geol. Surv. Prof. Paper 165c* (1931), pp. 83–134 (19 pls., 2 figs.).

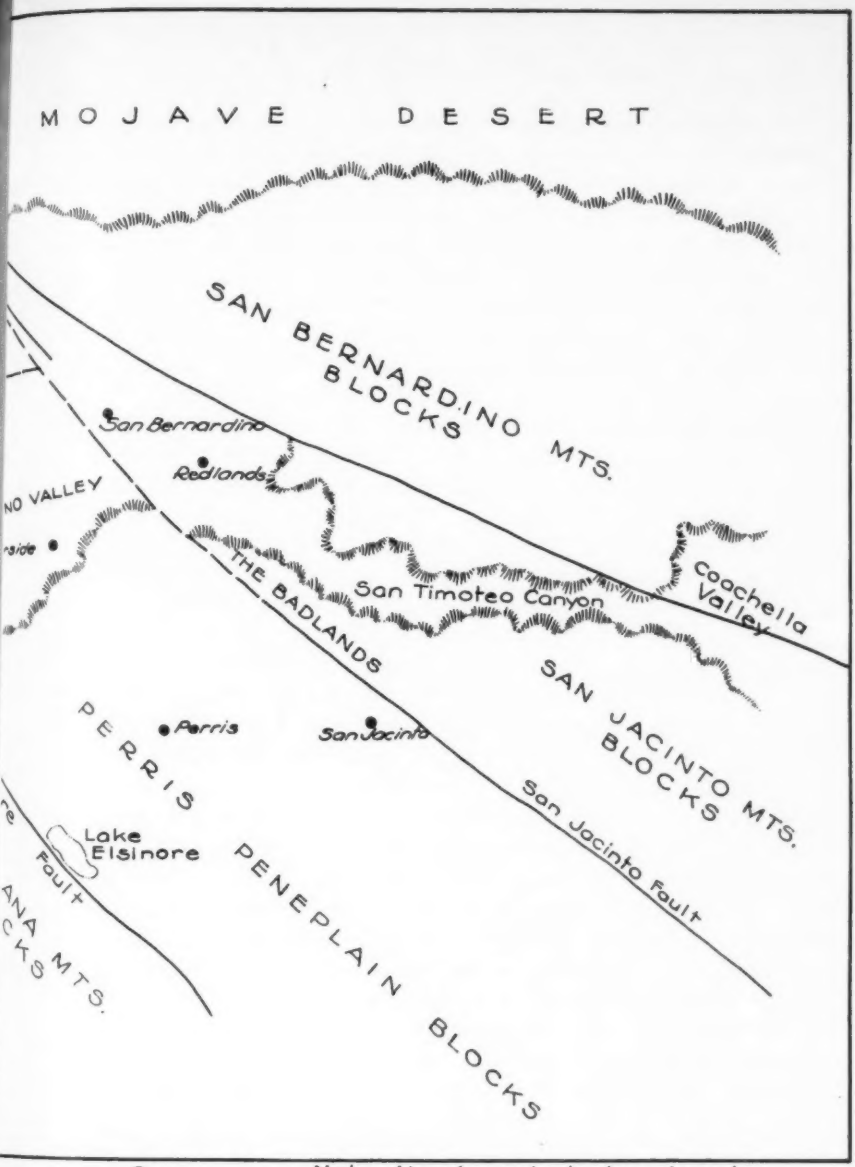


① Huntington Beach
② Newport
③ Seal Beach
④ Long Beach & Los Cerritos
⑤ Dominguez
⑥ Athens-Rosecrans
⑦ Inglewood
⑧ Beverly Hills
⑨ Salt Lake
⑩ Los Angeles
⑪ Whittier
⑫ Montebe
⑬ Santa Fe
⑭ Coyote
⑮ Fullerto

TECTONIC MAP OF THE

COMPILED BY

FIG. 16.—Tectonic map



Note- Numbered circles denote oil fields.

⑯ Olinda
⑰ Richfield
⑱ Torrance
⑲ Playa del Rey

Springs
n(E.Coyote)

: LOS ANGELES BASIN

B. L. CLARK

of the Los Angeles Basin

The northeast side of the Los Angeles basin may be taken as the Elsinore fault. This forms the eastern boundary of the marine Cretaceous and Tertiary deposits, which, in the area of the Santa Ana Mountains, are several thousands of feet thick, and are cut off abruptly at the Elsinore fault zone. The area to the northeast of this, labeled the "Perris Peneplane Blocks," is underlain by the older granitic and metamorphic rocks. This old surface is tilted toward the north and disappears in the alluvium of San Bernardino Valley. To the southwest the so-called "basin" area is bordered by the ocean.

The sediments exposed in the basin area, excepting a small area of Franciscan schist (Jurassic ?) in the San Pedro Hills block, are entirely of Cretaceous, Tertiary, and Pleistocene age. The only portion of the area where the Cretaceous and Eocene deposits are exposed is that between the Christianitos and Elsinore faults. In the Puente Hills area, north of the Whittier fault, Miocene deposits are known to rest upon a floor of basal complex. To the east of the Inglewood fault the Miocene deposits, as shown by well logs, rest directly upon the Franciscan series. In places the oldest deposits above the Franciscan are Upper Miocene in age; in other places the deposits are of Middle or Lower Miocene age.[17] In the area between the Inglewood and Whittier faults there is a much greater thickness of sediments than on the other side. In this area only a few oil wells have penetrated into Miocene deposits through Pliocene and Pleistocene sediments. Some of these wells are more than 5,000 feet deep. According to seismographic work by B. Gutenberg and J. P. Buwalda,[18] the sediments above the basal complex in this area are more than 8 miles thick. It is possible that Cretaceous and Eocene deposits underlie the Miocene sediments; however, it is not probable that they will be penetrated by a well.

Drilling and seismographic work have shown that the floor of deposition of the Los Angeles basin area, as a result of faulting, is irregular, that markedly different stratigraphic sequences are found

[17] William H. Corey, "Age and Correlation of Schist-bearing Clastics, Venice and Del Rey Fields," *Amer. Assoc. Petrol. Geol. Bull. 20*, No. 2 (1936), pp. 150–54.

[18] "Seismic Reflection Profile across Los Angeles Basin," *Geol. Soc. Amer. Proc. for 1935* (1936), pp. 327–28, abst.

on the different fault blocks, and that the changes in sequence take place fairly abruptly at the fault lines. Also evidence is accumulating which shows that the faults which bound the major blocks are older than the sediments which lie against their scarps. Some of the evidence for the old age of the faulting has been brought out by the recent seismographic surveys under Gutenberg and Buwalda,[19] their work showing that there is a much greater displacement of the lower sediments along the Inglewood fault than of those nearer the surface. Their work also shows that the Whittier fault is at least older than the Pliocene sediments.

It will be noted from the map (Fig. 16) that most of the principal folds in the Los Angeles basin area are closely associated with the faulting. The folding is very recent and is probably going on at the present time. It has been so rapid that in places the surface which existed before the folding is still fairly well preserved on the tops and sides of anticlinal hills. In some cases the folds are indicated only by the gentle upwarping of the alluvium. These are known as "topographic highs." Almost invariably they, like the larger folds, have been found to be associated with faulting.

Some of the best examples of the relation of folding to faulting in the Los Angeles basin are found along the Inglewood fault zone, which is not continuous on the surface but is, nevertheless, as shown by the well logs, a major fault zone along which there has been several thousand feet of displacement. As is shown on the map (Fig. 16) there is a series of these folds bordering the fault zone, nearly every one of which is the locus of an oil field.

Several geologists[20] have suggested that the folding along the Inglewood fault may have been brought about by horizontal shifting along a buried fault. This would imply that the folding was largely confined to the unbroken beds above the buried fault. Drilling in that area, however, does not bear out this hypothesis; the folding extends well down below the beds that overlie the fault zone. The hypothesis proposed by the writer is that this folding was brought about at a

[19] *Ibid.*

[20] J. E. Eaton, "Structure of the Los Angeles Basin and Environs," *Oil Age*, Vol. XX (December 1923), pp. 8–9 and 52, and Vol. XVI (1924), pp. 16–18, 52, 54; R. N. Ferguson and C. G. Willis, *Amer. Assoc. Petrol. Geol. Bull. 8*, No. 5 (1924), pp. 576–83 (2 figs.).

time of compression, as the result of the drag along the fault. Here, apparently, the horizontal movements have been much more important than the vertical. Much of the folding along the Inglewood fault matches very closely that produced in Experiments VI and VII. As will be noted from the map, some of the folds are on one side of the fault zone, some on the other; some of them are mere puckers, others are well-developed anticlines; some line up en echelon along the fault; they all die out in flat-lying beds at a comparatively short distance away from the fault. An examination of the folding along some of the other faults in this area shows the close relationship of the two. There are several folds along the Whittier and Christianitos faults and along the fault north of the Repetto Hills which are similar to those along the Inglewood fault. There is a series of small folds between the Whittier and Christianitos faults which, according to the mapping of W. A. English,[21] are associated with small discontinuous faults. The relationship of this folding to the faulting is quite obvious.

It will be noted from the map (Fig. 16) that certain folds are shown bordering questioned buried faults. These have not been established with certainty; however, the way in which the folds line up en echelon is taken as evidence that they have been formed along a fault which has not broken through to the surface. Under such a condition it would appear that horizontal shifting along the strike of the buried fault was the chief factor in the production of the folding at the time of compression. One of these questioned buried faults is shown on the east side of the San Gabriel Valley; along this line are several folds en echelon, which fade out to the east. The series of folds en echelon to the south and southeast of the town of Whittier is shown as bordering a questioned buried fault. In both these cases the evidence for the faulting is the arrangement of the folds. It is possible that the folds on the west side of the Torrence block were formed along a fault which is under the ocean but is close and parallel to the coast.

The Tertiary deposits of the Los Angeles basin area taken as a whole are not so intensely folded as those of the Ventura area which

[21] *Op. cit.*, Pl. I.

is just north of the Los Angeles basin, or as those found along the west and south sides of the San Joaquin Valley or in the Mount Diablo area. The folding over most of the Los Angeles basin area has been gentle and, of the two components of the movement along the faults, the horizontal has been more important than the vertical. In other areas the vertical movements have been the more important, as shown by the isolated synclines and the monoclinal folding along the San Joaquin Valley, and by the folding along the Riggs Canyon fault, to which references have already been made.

The type of folding found along the faults of the Los Angeles basin is very common along fault zones all over the world. Some of the best examples are in the Gulf states of the Mississippi Valley. One has only to examine the numerous structures, illustrated in the two volumes entitled *Typical American Oil Fields*, published by the American Association of Petroleum Geologists, to realize how large a part of the folding in the areas described originated along the sides of faults. In all these cases the folds fade out very quickly in going away from the fault. A large proportion of these folds are en echelon to the faults and most of them fade out into flat-lying beds in comparatively short distances from the faults.

MIDDLE DEVONIAN OF SOUTHERN INDIANA

D. G. SUTTON
Washington University
AND
A. H. SUTTON
University of Illinois

ABSTRACT

The Geneva dolomitic limestone of the northern portion of the southern Indiana Middle Devonian region, which formerly has been considered as either a lithologic facies of the Jeffersonville or Sellersburg limestones or both or a distinct formation older than the Jeffersonville, is shown by paleontologic and stratigraphic evidence to be a lithologic facies of the Jeffersonville. Since the Geneva and Jeffersonville are variations of the same geologic formation, the former name, by the custom of priority, should be applied to all the Indiana Devonian of Onondaga age. A direct sea connection between the northern and southern Indiana areas during Sellersburg time is postulated, and a new member of the Sellersburg formation is named.

INTRODUCTION

The Middle Devonian in the northern portion of the Devonian region of southern Indiana is represented by the Geneva formation. Farther south two other Middle Devonian formations, the Jeffersonville and Sellersburg limestones, occur. The Jeffersonville is unquestionably of Onondaga age, and the Sellersburg is Hamilton. The exact age and actual relationships of the Geneva to these two have never been determined satisfactorily. The Geneva has been thought to be a lithologic facies of either one or both of the southern units or a distinct formation older than the Jeffersonville. Ulrich[1] correlated it with the Schoharie although his reasons were not stated.

Stilson,[2] in 1818, referred to the burrstones on Sand Creek 60 miles from White River. These were undoubtedly from the Geneva, which crops out along Sand Creek in the vicinity of Scipio and to the northeast. He did not determine the stratigraphic position of the burrstones. In 1827 Lapham[3] described the rocks at the Falls of the Ohio

[1] E. O. Ulrich, "Revision of the Paleozoic Systems," *Geol. Soc. Amer. Bull. 22* (1911), p. 28.

[2] W. E. Stilson, "Sketch of the Geology and Mineralogy of a Part of the State of Indiana," *Amer. Jour. Sci.*, Vol. I (1818), pp. 131–33.

[3] I. A. Lapham, "On the Geology of the Vicinity of the Louisville and Shippingsport Canal," *Amer. Jour. Sci.*, Vol. XIV (1828), pp. 65–69.

without age designation. In 1841 Hall[4] referred all the limestone at the Falls of the Ohio to the Helderberg group of New York except a thin layer of water lime which he called "Onondaga." In 1843 Owen[5] correlated the black shale with the Marcellus and the limestone below with the Helderberg of New York. De Verneuil,[6] in 1848, mentioned the presence of Devonian rocks of Onondaga (Corniferous) age in Indiana and called them the "Cliff limestone."

Lyon and Cassidy,[7] in 1859, were the first to recognize any rocks of Hamilton age in Indiana. In 1860 Lyon[8] divided the beds at the Falls of the Ohio but did not give their geologic age. Borden,[9] in 1873, gave a brief description of the "Corniferous," Hydraulic, and Crinoidal limestones from Clark and Floyd counties. In 1874[10] he presented his report on Scott and Jefferson counties, and one year later[11] in his report on the "Geology of Jennings County" he correlated the Hydraulic and Crinoidal limestones, together with the New Albany shale, as Hamilton. In 1861 Collett[12] in a report on the "Geology of Shelby County" briefly described a buff magnesian limestone which he called "Geneva" and said was of "Corniferous" age without giving any paleontologic evidence of its Devonian age. In

[4] James Hall, "Notes upon the Geology of the Western States," *Amer. Jour. Sci.*, Vol. XLII (1843), p. 58.

[5] D. D. Owen, "On the Geology of the Western States," *Amer. Jour. Sci.*, Vol. XLII (1843), pp. 151–52, 161–62.

[6] E. de Verneuil, "Classification of Paleozoic Rocks of Ohio, Kentucky, and Indiana," *Amer. Jour. Sci.* (2d ser., 1848), pp. 159–370.

[7] S. S. Lyon and S. A. Cassidy, "A Description of Nine New Species of Crinoidea from the Subcarboniferous Rocks of Indiana and Kentucky," *Amer. Jour. Sci.* (2d ser.), Vol. XXVIII (1860), p. 244.

[8] S. S. Lyon, "Remarks on the Stratigraphical Arrangement of the Rocks of Kentucky, from the 'Cateripora escharoidea' Horizon of the Upper Silurian Period in Jefferson County, to the Base of the Productive Coal Measures in the Eastern Edge of Hancock County," *Trans. St. Louis Acad. Sci.*, Vol. I (1860), pp. 612–21.

[9] W. W. Borden, "Report of a Geologic Survey of Clark and Floyd Counties," *Ind. Geol. Surv. 5th Ann. Rept.* (1873), pp. 134–89.

[10] "Geology of Scott and Jefferson Counties," *Ind. Geol. Surv. 6th Ann. Rept.* (1874), pp. 112–86.

[11] "Geology Report of Jennings County," *Ind. Geol. Surv. 7th Ann. Rept.* (1875), pp. 146, 180.

[12] John Collett, "Geology of Shelby County," *Ind. Dept. Geol. and Nat. Hist. 11th Ann. Rept.* (1881), pp. 55–88.

1896 Newsom[13] mapped a section across southern Indiana and discussed briefly the Devonian rocks. He amplified the discussion in the *Indiana Survey Report* of 1901.[14]

In 1897 Foerste[15] described the Devonian rocks at various points in Indiana but made no correlations. The Shelby bed from Shelby County, which he described but did not correlate, was later reported by Kindle in 1900 as the same as Collett's Geneva limestone. Kindle[16] in 1899 published a report of his work on the Devonian and Lower Carboniferous faunas of southern Indiana. He applied the names "Jeffersonville" and "Sellersburg" to the Devonian formations below the black shale, the lower formation being approximately the earlier "Corniferous" limestone and the upper the combined Hydraulic and Crinoidal limestones. In the following year he[17] issued a much more detailed report on the Devonian fauna and stratigraphy of Indiana but contributed nothing further to our knowledge of the exact age of the Geneva.

In 1900 Siebenthal[18] described the Silver Creek limestone of southern Indiana and briefly the geology of the region. He applied the name "Silver Creek" to the Hydraulic limestone, which was the basis of the early cement industry of southern Indiana, and restricted Sellersburg to the crystalline limestone which overlies the cement rock. In 1915 Butts[19] gave the name "Beechwood" to the crystalline limestone above the Silver Creek in Jefferson County, Kentucky. This name is now used in Indiana also. Later usage has restored the

[13] J. F. Newsom, "A Geologic Section across Southern Indiana from Hanover to Vincennes," *Jour. Geol.*, Vol. VI (1898), pp. 250–56.

[14] "A Geological Section across Southern Indiana from Hanover to Vincennes," *Ind. Dept. Geol. and Nat. Hist. Res. 26th Ann. Rept.* (1901), pp. 227–303.

[15] A. F. Foerste, "A Report on the Niagara Limestone Quarries of Decatur, Franklin, and Fayette Counties, with Remarks on the Geology of the Middle and Upper Silurian Rocks of These and Neighboring (Ripley, Jennings, Bartholomew, and Shelby) Counties," *Ind. Dept. Geol. and Nat. Hist. Res. 22d Ann. Rept.* (1897), pp. 195–255.

[16] E. M. Kindle, "The Devonian and Lower Carboniferous Faunas of Southern Indiana and Kentucky," *Amer. Paleont. Bull. 12*, Vol. III (1899), p. 111.

[17] "The Devonian Fossils and Stratigraphy of Indiana," *Ind. Dept. Geol. and Nat. Hist. Res. 25th Ann. Rept.* (1900), pp. 538–758.

[18] C. E. Siebenthal, "Silver Creek Hydraulic Limestone of Southeastern Indiana," *Ind. Dept. Geol. and Nat. Hist. Res. 25th Ann. Rept.* (1900), pp. 331–89.

[19] Charles Butts, "Geology and Mineral Resources of Jefferson County, Kentucky," *Ky. Geol. Surv.*, (4th ser.), Vol. III, Part II (1914–15), p. 270.

name "Sellersburg" to its original meaning—to designate all the limestone between the Jeffersonville limestone and the New Albany black shale—and has established Silver Creek and Beechwood as members of the Sellersburg.

No detailed study involving the Geneva formation has been made since Kindle's work in 1899. During the summer of 1935 we examined the Middle Devonian rocks of southern Indiana throughout their area of occurrence. Many sections were measured, and fossil collections made. Many more exposures have been studied than heretofore because of their present availability through the opening of many new quarries and exposures developed by the building of state highways through the area, especially in the critical central portion where the relation of the Geneva to the Jeffersonville is best shown. Identification of some of the fossils has been checked by Professor T. E. Savage, of the University of Illinois, and all of them by Mr. D. K. Gregor, of Washington University. As a result of these studies, we consider the Geneva a lithologic facies of the strata called Jeffersonville in the south portion of the area and definitely Onondaga in age.

LOCATION AND EXTENT OF THE AREA

The Middle Devonian area of southern Indiana embraces parts of Clark, Scott, Jefferson, Jennings, Bartholomew, Decatur, and Shelby counties and extends from New Albany and Jeffersonville on Ohio River northward to Geneva on Flatrock Creek in the southern part of Shelby County. It is a relatively narrow area, 85 miles long and 8–10 miles wide, located in parts of townships 7, 8, and 9 east of the second principal meridian. The general location is shown in Figure 1. The Devonian formations are covered in all but the southernmost part by a thin deposit of Illinoian glacial till in the interstream areas. Outcrops of the Devonian rocks occur along the tributaries of the east fork of White River, and good exposures are present in many quarries and road cuts.

CHARACTER AND RELATIONS OF THE FORMATIONS

Although the chief problems involved are the age and relations of the Geneva to the other Middle Devonian formations it is necessary for their solution that the other formations be described briefly.

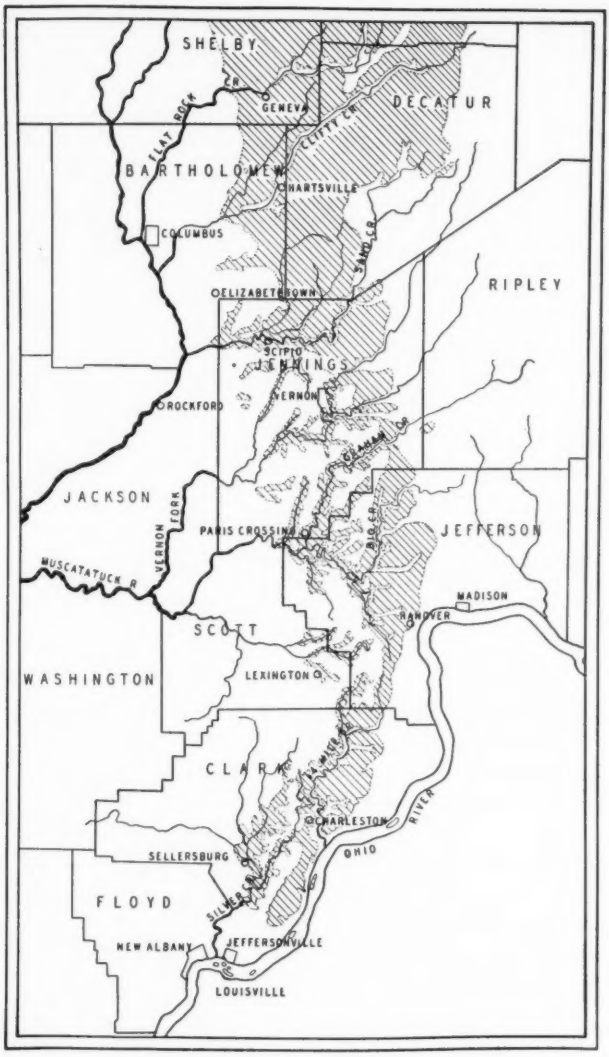


FIG. 1.—Areal geology of the Middle Devonian of southern Indiana. (After State Geological Map of Indiana.)

Jeffersonville.—This formation was named from its type locality at the Falls of Ohio River between Jeffersonville and the mouth of Silver Creek.[20] The formation is a gray to bluish-gray, highly crystalline, hard, compact, relatively pure limestone which breaks with an uneven fracture. It is usually thickly bedded and weathers into a characteristic red clay. The upper few feet are more thinly bedded than the lower portion. The formation is abundantly fossiliferous and contains two prominent fossil zones. The fossil coral "reef" or bioherm for which the Falls of the Ohio have long been noted occurs in the lower part of the Jeffersonville. These corals are so well known that further descriptions are unnecessary. *Spirifer gregarius* and *S. acuminatus* are abundant and characteristic of the beds above the coral zone. *S. gregarius* is the most abundant fossil in the middle portion and *S. acuminatus* of the upper part of the formation. Other common and characteristic Onondaga species occur. The reader is referred to the works of Kindle and Butts for lists of these.

The Jeffersonville type of rock is about 20 feet thick at Ohio River, increases to 31 feet near Sellersburg, and decreases toward the north until it disappears from the section north of Burnsville, $6\frac{1}{2}$ miles northeast of Elizabethtown. In the area where the Geneva type of rock occurs below typical Jeffersonville, no definite contact can be noted between them, the two grading from one into the other. The Jeffersonville is usually more bluish in color and more coarsely crystalline and does not possess the dolomitic character of the Geneva, which has a mottled appearance in contrast to the more or less homogeneous Jeffersonville. The Jeffersonville lies disconformably on the Middle Silurian Louisville limestone and is overlain disconformably by the Sellersburg. It grades laterally into the Geneva.

Sellersburg.—This name was proposed by Kindle in 1899 to include all the beds between the Jeffersonville limestone and the New Albany black shale. The terms "Silver Creek" and "Beechwood" are now considered as names of members of the Sellersburg. The Silver Creek received its name from its occurrence in the vicinity of Silver Creek, Clark County, Indiana, and the Beechwood from Beechwood

[20] "The Devonian and Lower Carboniferous Faunas of Southern Indiana and Central Kentucky," *loc. cit.*, p. 8.

station on the Louisville and Nashville Railroad in Kentucky. The Silver Creek member is a gray, fine-grained, thinly bedded, argillaceous limestone which takes on a shelly appearance upon weathering. It is not so hard as the beds above and below. In Speeds quarry, near Sellersburg, there is a shaly limestone 18 inches thick below the typical Silver Creek cement rock, which is also included in the Sellersburg on the evidence of *Spirifer audaculus*. We are proposing the name "Speeds" to designate this member. The Silver Creek is 16 feet and 10 inches thick in the quarry, diminishes in thickness toward the north, and disappears about 3 miles north of Lexington.

The Beechwood is a light-gray to dark-blue, coarsely crystalline, massive limestone with abundant crinoidal fragments. Near the base of the limestone there is generally a conglomeratic band marked by small polished black pebbles. The Beechwood is about 4 feet thick in the quarry near Sellersburg and decreases in thickness toward the north. The entire Sellersburg loses its characteristic lithologic features about 35 miles north of the Falls of the Ohio and northward can be separated from the underlying Jeffersonville only on paleontologic evidence. The Sellersburg has been identified as far north as Burnsville.

The Hamilton age of the Sellersburg is well established by the faunal content. For lists of the common and characteristic Hamilton fossils of the formation the reader is referred to Kindle's[21] report. Only one point in connection with the Sellersburg paleontology need be mentioned. Kindle stated that *Spirifer pennatus*, which is common in the Sellersburg of northern Indiana, is unknown in southern Indiana,[22] and because of its supposed absence postulated no connection between the Sellersburg seas in the two areas. This species was collected from the Sellersburg of the southern area in the vicinity of North Vernon thus admitting the probability of a direct sea connection between the two areas as is to be expected.

Geneva.—This formation was named from its occurrence at Geneva in Shelby County.[23] Here it is a dark-buff to brownish, soft to hard, fine-grained magnesian limestone. It is nearly white to cream colored in certain localities and fairly hard on unweathered surfaces. The texture varies from fine-grained saccaroidal to coarsely

[21] *Ibid.*, pp. 540–41. [22] *Ibid.*, p. 562. [23] Collett, *op. cit.*, pp. 55–88.

crystalline. It is usually porous and in places, especially in the type locality, concentrations of calcite are abundant in the cavities. In the northern portion of the area the lower part of the Geneva dolomite is thickly bedded and massive and is predominantly a buff to chocolate brown. The upper portion, 6–8 feet, is commonly thinly bedded locally, in layers 2–3 inches thick. Locally, the formation is very cherty and weathers to a white chalky material. Along Wyloosing Creek north of Scipio is a layer of cherty material about 2 feet thick which has been referred to as the burrstone layer. The basal portion of the Geneva is highly dolomitic, but the percentage of magnesium decreases toward the top. There is also a decrease in the dolomite content toward the south and west, away from the old shore line. Fossils are rare near the base, especially toward the north, and those that do occur are casts and molds. The burrstone layer contains many casts and molds. Near the top of the formation fossils are abundant but usually poorly preserved.

Beds of the Geneva type of rock appear in the section below typical Jeffersonville limestone in the vicinity of Lexington, where 3 feet of strata may be assigned to it. Northward the Geneva type of rock thickens as the Jeffersonville thins. There are 30 feet exposed at Geneva. North of this locality it is deeply buried by glacial till. The greatest known thickness occurs along the east side of Bear Creek in the NW. $\frac{1}{4}$ of the SW. $\frac{1}{4}$ of Sec. 30, T. 8 N., R. 8 E., where it is 62 feet thick. The presence at the top of the section here of thin beds with *Spirifer acuminatus* and *Stropheodonta hemispherica* indicates that not much if any of the formation is missing. These brachiopods and their associated forms are found wherever the upper part of the Geneva or Jeffersonville is exposed.

The coral fauna is not exposed so frequently as the brachiopod zone since the former is near the base of the formation. The coral zone is exposed in the Jeffersonville limestone at the Falls of the Ohio, in Speeds quarry near Sellersburg, and in a quarry southeast of Charlestown. Thirty miles north of Charlestown, where the Geneva crops out in a ravine northeast of Deputy, the same coral species occur in abundance. They are also exposed in a quarry south of Paris and again west of the same town south of the bridge across Graham Creek on State Highway No. 3. The same fauna occurs be-

low a cherty member on State Highway No. 7 north of the bridge across Graham Creek. The fossils are found about 15 feet above the base of the Geneva south of Vernon.

The occurrence of these characteristic Jeffersonville (Onondaga) fossil zones in approximately the same stratigraphic positions in the Geneva as well as the lateral gradation between the beds of the two units is ample proof of the contemporaneity of deposition of the two. Both Jeffersonville and Sellersburg rocks are exposed in the northern Indiana Middle Devonian region in the portion of Wabash Valley between Peru and Delphi and along Tippecanoe River near Monticello. No Geneva type of rock occurs here. Only detailed subsurface data will show where the Geneva type of rock gives way to the more typical limestone known as Jeffersonville in the north area.

COLUMNAR SECTIONS

The following stratigraphic sections, arranged from south to north, are given to show the faunal zones and the relations of the Geneva to the other Middle Devonian strata of the region and to support the conclusion that the Geneva and Jeffersonville are lithologic facies of the same geologic formation.

TABLE 1

QUARRY, 0.85 MILES, SOUTHEAST OF THE RAILROAD STATION AT SELLERSBURG IN THE NW. ¼ OF LOT NO. 90

	Thickness
6. New Albany black shale	
5. Beechwood, Upper Sellersburg; massive, coarsely crystalline, abundant crinoid remains fragments of *Stropheodontas* and *Rhipidomellas;* lower 3 inches with shiny black pebbles	4 ft.
4. Silver Creek, Middle Sellersburg; upper 5½ feet in thick layers, lower part shelly, thin-bedded, argillaceous limestone, fine-grained	16 ft., 10 in.
3. Speeds, Lower Sellersburg; bluish shaly limestone, very fossiliferous	1 ft., 6 in.
2. Jeffersonville; gray, crystalline limestone, lower part massive, upper part thin-bedded. Coral zone in lower part. *Spirifer gregarius* above and *S. acuminatus* in upper part	30 ft., 9 in.
1. Louisville, Silurian; limestone	4 ft. exposed.

TABLE 2

QUARRY SOUTHEAST OF LEXINGTON, IN NW. ¼ OF SE. ¼ OF SEC. 34, T. 3 N., R. 8 E. ON THE NORTHEAST SIDE OF THE RAILROAD

		Thickness
6.	New Albany shale	
5.	Beechwood; coarsely crystalline, hard limestone. Not very fossiliferous	1 ft. to 9 in.
4.	Silver Creek; fine-grained argillaceous limestone, no fossils found	5 ft.
3.	Probably Jeffersonville; crystalline, tan colored, fossil fragments	2 ft.
2.	Jeffersonville; bluish-gray, compact, crystalline, hard limestone	7 ft., 6 in.
1.	Geneva; yellowish dolomitic limestone, *Spirifer acuminatus* and large *Stropheodontas* exposed	3 ft.

TABLE 3

ONE MILE NORTH OF DEPUTY ON THE NORTH BANK OF BIG CREEK ALONG THE EAST SIDE OF HIGHWAY NO. 3

		Thickness
3.	Sellersburg; blue, crystalline limestone, not very fossiliferous.	3 ft.
2.	Jeffersonville; blue gray, beds 6–10 inches, thinner toward base, no definite contact with underlying beds	15 ft.
1.	Geneva; buff to gray, highly dolomitic in lower part, fine-grained near top. *Spirifer acuminatus* zone near top	22 ft.

TABLE 4

TWO MILES SOUTH OF PARIS CROSSING AND 2 MILES WEST OF DEPUTY; QUARRY ON THE WEST BANK OF MUSCATATUCK RIVER IN SEC. 7 IN THE NW. CORNER OF JEFFERSON COUNTY

		Thickness
4.	New Albany shale	
3.	Sellersburg; dark-blue, hard, crystalline limestone in massive layers. One to 2 inches of soft shaly material at base	7 ft., 8 in.
2.	Jeffersonville; light-blue, crystalline, massive limestone	8 ft.
1.	Geneva; buff to light brown, crystalline, dolomitic limestone base not exposed	4 ft.

TABLE 5

SOUTHEAST OF VERNON, SOUTH OF THE INTERSECTION OF STATE HIGHWAYS 7 AND 3 IN THE CENTRAL PART OF SEC. 11, T. 6 N., R. 8 E., ALONG EAST SIDE OF HIGHWAY NO. 3

		Thickness
3.	Sellersburg; dark blue to gray, coarsely crystalline, massive limestone	1 ft., 11 in.
2.	Jeffersonville; light blue to gray, not as crystalline as Sellersburg	4 ft.
1.	Geneva; upper 14 feet light buff, thin-banded, fine-grained, fossiliferous dolomite with *Spirifer acuminatus* and *Stropheodonta hemispherica*. Below this a 3–4-inch clay seam with some corals. The lower 22 feet is a fine-grained, buff-colored dolomite with a prominent coral zone about 15 feet above the base	42 ft., 4 in.

The Geneva is 53½ feet thick along the east bank of Muscatatuck River at the bridge on United States Highway No. 50 east of North Vernon. In the central portion of Sec. 6, T. 7 N., R. 8 E., in the southwest bluff of Sand Creek there are 36 feet of buff to chocolate colored, non-fossiliferous Geneva overlying Louisville limestone. From the bed of Bear Creek east to the top of the hill across the road in the NW. ¼ of the SW. ¼ of Sec. 30, T. 8 N., R. 8 E., the Geneva is 62 feet thick. The lower 22 feet is fine-grained, non-fossiliferous, buff to chocolate dolomite; 26 feet are concealed, and the upper 14 feet is a light gray, fossiliferous, thin-bedded, cherty dolomite. This portion of the section contains *Spirifer acuminatus*, *Stropheodonta perplana*, *Stropheodonta hemispherica*, and *Chonetes* sp.

TABLE 6

CLYDE HUSTON QUARRY, NE. ¼ OF NW. ¼ OF SEC 5, T. 8 N., R. 7 E., ALONG THE EAST SIDE OF THE RILEY HIGHWAY NORTH OF LITTLE SAND CREEK

	Thickness
4. New Albany shale	
3. Sellersburg; dark-blue, hard, crystalline limestone	10 in.
2. Jeffersonville; gray, hard, crystalline limestone	1 ft., 4 in.
1. Geneva; light-gray to buff, fossiliferous limestone, dolomitic in part. Upper 6–8 feet in thin beds, 2–5 in. Lower part massive	19 ft.

TABLE 7

SOUTH OF GENEVA (SULPHUR HILL) ALONG THE NORTHWEST BANK OF FLAT CREEK IN THE SOUTHERN PART OF SHELBY COUNTY; TYPE LOCALITY OF THE GENEVA

	Thickness
2. Geneva; buff to cholocate, fine-grained, dolomite. Hard in places, concentrations of calcite in cavities. Fossils rare, occurring as casts and molds. Following species obtained: *Ambocoelia umbonata*, *Conocardium ohioensis*, *C. trigonale*, *Meristella nasuta*, and *Nucleospira concinna*. Exposed about	30 ft.
1. Louisville limestone	

Many other sections have been studied, but these are sufficient to illustrate the features of the Geneva which demonstrate its transitional relationship to the Jeffersonville.

CONCLUSIONS

The detailed field study of the Middle Devonian formations of southern Indiana justifies the following conclusions:

1. The Geneva is a northward lithologic facies of the Jeffersonville formation of Onondaga age as shown by the Onondaga faunules of the Jeffersonville, which continue into the Geneva at the same horizons and by the lateral transition from the dolomitic Geneva limestone to the purer Jeffersonville limestone. This gradation begins farthest south in the lowest beds and reaches the progressively higher beds toward the north, which makes it appear upon casual investigation that the Jeffersonville thins toward the north, the thinning being accompanied by a corresponding thickening of the Geneva.

2. If this conclusion is valid, the term "Jeffersonville" is a synonym of "Geneva," and by the custom of priority the latter name should be applied to all the Indiana rocks of Onondaga age.

3. The presence of *Spirifer pennatus* in the Sellersburg formation of southern Indiana suggests the probability of a sea connection between the northern Indiana and southern Indiana Sellersburg areas during Hamilton time contrary to earlier expressed opinions.

4. If the "Beechwood" and "Silver Creek" are to be classed as members of the Sellersburg in the extreme southern portion of the area, then the shaly limestone which lies between the Jeffersonville and Silver Creek and which by its faunal content is Hamilton and must be classed as part of the Sellersburg, is also worthy of member designation. We propose to call it the "Speeds" member of the Sellersburg.

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TABLE 6

CLYDE HUSTON QUARRY, NE. ¼ OF NW. ¼ OF SEC 5, T. 8 N., R. 7 E., ALONG THE EAST SIDE OF THE RILEY HIGHWAY NORTH OF LITTLE SAND CREEK

	Thickness
4. New Albany shale	
3. Sellersburg; dark-blue, hard, crystalline limestone	10 in.
2. Jeffersonville; gray, hard, crystalline limestone	1 ft., 4 in.
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FOSSIL ALGAE FROM THE KUNDELUNGU SERIES OF NORTHERN RHODESIA[1]

BURTON EDWARD ASHLEY
University of Minnesota

In a petrographic study of some rock sections from the Lake Tanganyika district of Northern Rhodesia, Africa, the writer found algal forms. The fossils occur in the Kundelungu series, which is probably of pre-Cambrian age.

The sample was obtained from the west side of Mutondwe Island, which lies near the south end of Lake Tanganyika, about two and one-half miles north and slightly east of the port of Mpulungu. The rock is a pyritic black chert, conformably overlying a feldspathic sandstone, both of which belong to the Kundelungu series. The beds strike nearly straight north and dip about 10° west. The chert is very fine grained, with minor amounts of sericite and introduced carbonate. Slight fracturing has occurred, with subsequent cementation.

Figure 1 clearly shows the algal forms. Professor Josephine Tilden, phycologist at the University of Minnesota, examined the structures and drew attention to the fact that they are very similar in appearance to *Lyngbya ochracea*, an iron-secreting alga that lives today.

The Kundelungu series is now generally correlated with the upper part of the pre-Cambrian Katanga system of the Belgian Congo, but as this assignment of age is a moot point, a short review of the opinions of various students is desirable. The early students of the Kundelungu (Cornet, Studt, Robert)[2] placed it in the Karroo, the age of which has been variously determined from Permian to Jurassic.[3]

[1] Published with the permission of the British South Africa Co.

[2] Maurice Robert, "La Stratigraphie du système Kundelungu au Katanga," *Annales de la Société Géologique de Belgique. Publications relatives au Congo Belge et aux régions voisines.* Annexe au Tome 39 des Annales (1912).

[3] J. A. Bancroft and R. A. Pelletier, "Notes on the General Geology of Northern Rhodesia," XII *Intl. Geol. Cong. Guidebook, Ex. C 22* (Pretoria, 1929).

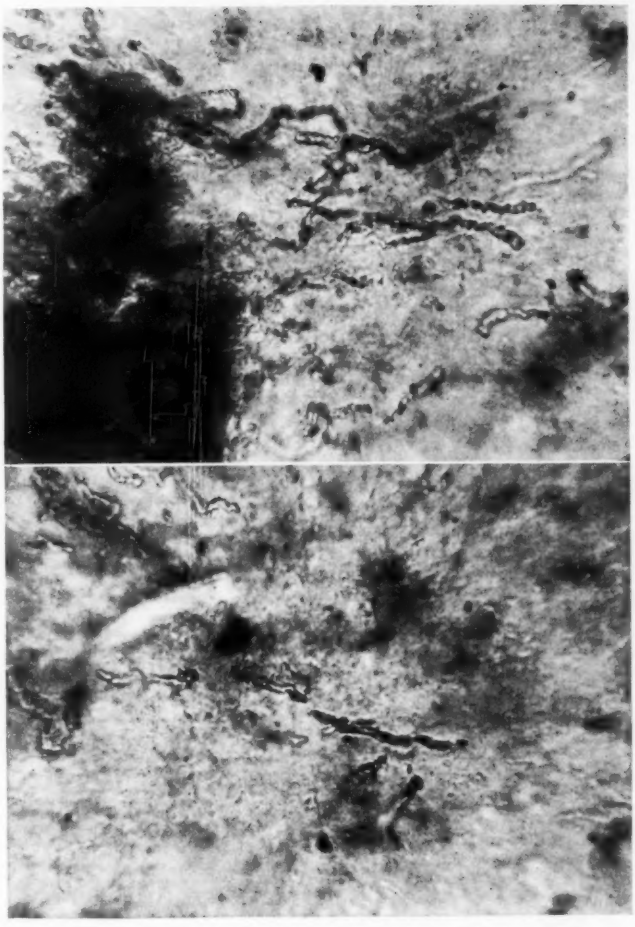

FIG. 1.—Photomicrographs of fossil algae similar to *Lyngbya ochracea*, ×900. Photo by Henrici.

As more extensive studies were made, the Kundelungu was placed farther back in the geologic column. In 1913 Studt[4] put the Tanganyika sandstones (as he called the Kundelungu) in the Transvaal system, which is pre-Devonian.[5]

Later, Robert said that the Kundelungu and the underlying Schisto-Dolomitique system are older than the Permian, but that it is not possible to determine their ages with precision.[6]

Schuchert places the Kundelungu in the late Proterozoic,[7] while Gregory[8] says that the Tanganyika sandstone is Archeozoic.

Two very recent papers offer conflicting evidence. Veatch,[9] in discussing the age of the Kundelungu, draws attention to the fact that there is no angular unconformity between it and the underlying Séries de Mines. The Kundelungu beds, which are unmetamorphosed on the plateau near Lake Tanganyika, are involved in the Katanga folding farther west. According to Veatch, the mineralization which occurred during, or subsequent to, this folding has an age of over six hundred million years as determined by means of the lead-uranium ratio. Since a similar determination on beds known to be upper Cambrian gives an age of four hundred and fifty million years, this would definitely place the Kundelungu in the pre-Cambrian.

The other paper was written by Ghitulescu,[10] who reports that his party found a coral under the lower Kundelungu in the upper group of the Schisto-Calcaire. Although the coral is unidentifiable because it is poorly preserved, it could hardly be as old as pre-Cambrian.

It is reported that a fossil identified as Collenia was found in the

[4] F. E. Studt, "Geology of the Katanga and Northern Rhodesia," *Trans. Geol. Soc. So. Africa*, Vol. XVI (1913), p. 64.

[5] Alexander du Toit, *The Geology of South Africa* (Edinburgh, 1926).

[6] "Carte géologique du Katanga" (1931).

[7] Charles Schuchert, "The Congo Basin in Its Relation to the Rest of Africa," *Amer. Jour. Sci.*, Vol. XXI (January, 1936).

[8] J. W. Gregory, *The Rift Valleys and Geology of East Africa* (Seeley Service, 1921).

[9] A. C. Veatch, "Evolution of the Congo Basin," *Geol. Soc. Amer. Mem. 3* (August, 1935).

[10] T. P. Ghitulescu, "Une Mission d'exploration au Moyen Congo," *Buletinul Societatii Romane de Geologie*, Vol. II (Bucarest, 1935).

upper Lumpungu series, which may be of lower Kundelungu age.[11] However, details are lacking.

If the age of the Kundelungu is taken to be pre-Cambrian, as seems to be the opinion of most men who know it, the algal occurrence, though by no means unique, does afford one more example of pre-Cambrian life.[12]

ACKNOWLEDGMENTS.—The writer wishes to express his thanks to Professors Josephine Tilden, Frank Grout, and J. W. Gruner for valuable assistance. Dr. A. T. Henrici, department of bacteriology, did the photographic work.

[11] *African Geol. Surv. So. Equatorial Sec., Proc. of the First Meeting* (July, 1931), p. 15.

[12] C. D. Walcott, "Notes on Fossils from Limestones of Steeprock Lake, Ontario," *Geol. Surv. Can. Mem. 28* (1912), p. 16; *idem*, "Pre-Cambrian Algonkian Algal Flora," *Smithsonian Inst. Misc. Coll.*, Vol. LXIV, No. 2 (1914); E. S. Moore, "The Iron Formation of Belcher Islands, Hudson Bay, etc.," *Jour. Geol.*, Vol. XXIV (1918), pp. 412–38; F. F. Grout and T. M. Broderick, "Organic Structures in the Biwabik Iron-bearing Formation of the Huronian of Minnesota," *Amer. Jour. Sci.*, Vol. XLVIII (1919), p. 199; J. W. Gruner, "Algae Believed To Be Archean," *Jour. Geol.*, Vol. XXXI (1933), pp. 146–48.

LETTER TO THE EDITOR

In your comment on *East African Plateaus and Rift Valleys*, which I recently received in Java, you note correctly that I regard the extensive plateau of East Africa and its peripheral rift valleys as a single structure, produced by the development of an underlying asthenolith. And you inquire what relation, if any, I would infer to exist between that centralized structure and the great meridional, north-south plateau belt that seems to reach from northern Abyssinia to the Zambezi.

In response I would state as a fact that there is no such meridional structure. There are three elevated but separate plateau regions of similar altitude and extent and one much lower and less extensive. They are: (*a*) the Abyssinian Plateau, bounded on the northeast by the Danakil depression (presumably a true sunken trough or "rift valley"), on the southeast by the Lake Stephanie–Djibouti rift valley, on the southwest by a downwarp that extends from Lake Rudolph to the Nile Sudd, and on the west by the Sudd itself. The last-named downwarp separates Abyssinia completely from the East African Plateau; (*b*) the East African Plateau, which carries Lake Victoria and is defined chiefly by the eastern and western arcs of the so-called "rift" valleys and which it will be convenient to distinguish as the Nyanza structure;[1] (*c*) the Rhodesian Plateau, south of the Rukwa rift valley and west of the Luangwa depression; (*d*) the volcanic plateau east of Lake Rudolph and sloping gently to the Indian Ocean.

Each of these four areas is, I think, a distinct structure. I have not studied them on the ground, as I have the Nyanza structure, and I would deem it hazardous to extend the hypothetical explanation of that uplift to the other three without observation in the field. However, from casual observations along their margins and from descriptions, I would guess that (1) the Abyssinian Pla-

[1] Bailey Willis, *Geologic Structures* (2d ed.; New York: McGraw-Hill Book Co., 1929).

teau is an uplift over an active asthenolith, very similar to that which I postulate as underlying the Nyanza structure but unlike it in that the lava has escaped by fissure eruptions over the basin itself and special structures have resulted therefrom; (2) the Rhodesian Plateau may be raised by the growth of an asthenolith, but, if so, the magma lies at such a depth that there is no surface evidence of its existence, except the fact of uplift; (3) the volcanic plateau east of Lake Rudolph combines features of fissure eruptions and volcanoes and clearly represents a heated source, but it is not elevated as a plateau and I would guess that the concentration of heat and melting had been relatively superficial, as compared with the greater depths of the supposed asthenoliths beneath the other three areas.

The four plateaus thus distinguished are areal, not linear, elements of the earth's crust. One might liken them in dimensions to the Great Basin region of the West. The linear concept can be applied only to their peripheries, where the curvature is slight, and the notion of continuity may be traced to their approach to one another where they line up as tangent curves. This apparent connective appealed to the imagination of Suess—4,000 miles of it! It was imposing, it imposed itself upon him and through him upon our science, but it is not real. Let us note the gaps.

The Ruaha Valley, the southeastern element, is separated from the southern end of the Gregory or Great Eastern rift valley by an unbroken expanse of high plateau, 80 miles across. The Gregory rift valley, in turn, ends on the north in the local grid structure of Lake Baringo, and between it and Lake Rudolph is an extensive plain, the further limits of which lay beyond my horizon as I looked over it from an elevation of 4,000 feet. It is 100 miles or more across. The Lake Rudolph trough seems to extend north into the Abyssinian Plateau in the Onebo Valley, but not northeast to Lake Stephanie; here, however, I depend on maps as I have not seen the region.

Any depression skirting the southern margin of the Abyssinian Plateau must, of course, lead to the Red Sea, but that wide trough is, I think, quite unlike the rift valleys in origin. It lies between the African and the Arabian continental elements or masses. They are essentially granitic and were, I take it, separately intruded into

the outer crust. Between them remained a strip of the more basic crust which they intruded, and it, by virtue of greater density, maintained a relatively low level. That, I suggest, may be the origin of the Red Sea. Its margins are now defined by normal faults and flexures in consequence of the uplifts of the adjacent masses, but those are relatively young structures.

There remains the Araba–Dead Sea–Jordan link in the chain. New light has been thrown upon its structure by the work of Mr. F. E. Wellings, chief geologist of the Iraque Petroleum Company, who after seven years of detailed surveying in Palestine, the Araba–Dead Sea section, and Transjordania in 1934 wrote me of his observations, which demonstrate post-Eocene folding combined with a clockwise rotation of the Palestine block. The Dead Sea faults may thus be regarded as strike-slip faults, developed simultaneously with anticlines and synclines whose axial trends have a northeasterly trend and are cut off by the faults. The evidence is presented with Mr. Wellings' permission in a paper on "Some Fault Troughs," which is now in the hands of the Geological Society of America for publication. The Dead Sea trough thus appears to be neither rift valley nor ramp valley, though perhaps more of a ramp structure than of a rift structure.

Thus the great meridional rift, the child of Suess's imagination and the basis of much-discussed theories, seems to resemble the sea serpent in that it consists of certain curves whose connection is hypothetical.

BAILEY WILLIS

STANFORD UNIVERSITY, CALIFORNIA

REVIEWS

Geology of the Tampico Region, Mexico. By JOHN M. MUIR. Tulsa, Oklahoma: American Association of Petroleum Geologists, 1936. Pp. 280; figs. 41; pls. 15; and tables 9. 6×9 inches. Cloth. $3.50 to A.A.P.G. members and associates in good standing; $4.50 to others.

Here is a source book on the geology of a large and economically important part of Mexico. It treats in a comprehensive way the stratigraphy, structure, and history of oil development of the rich petroliferous area in southern Tamaulipas and northern Vera Cruz. All earlier publications dealing with the geology of the district are summarized in this volume and a very large amount of new data is added from field and laboratory studies by the author and by many other geologists. Extensive faunal lists are the basis for the age assignment of each formation. The work is excellently illustrated with maps, cross sections, columnar sections, and pictures, including an areal geologic map of the Coastal Plain, extending from the eastern front of the Sierra Madre cordillera to the Gulf of Mexico in a belt about two hundred miles long parallel to the coast in the vicinity of Tampico and Túxpan.

The stratigraphic section discussed begins with Lower Mississippian sandstone and shale which rest unconformably on schist and gneiss of probably pre-Cambrian age. Permian black shale with thin beds of sandstone is separated by unconformities from the underlying Mississippian and overlying Triassic. The latter consists of red sandstones and shales with a conglomerate of quartz pebbles at its base. These beds, exposed in the Sierra Madre Oriental, probably underlie the Coastal Plain but have not been recognized in the samples from the oil fields. A great unconformity at the top of the Triassic marks the contact with a thick limestone series of Jurassic and Cretaceous age.

In the northern oil fields, Jurassic limestones were recognized in three wells and Lower Cretaceous in two. The Middle Cretaceous has two lithologic facies distributed in different areas: (1) a reef facies, the El Abra limestone, which produces oil in the Southfields; and (2) a deep-water facies, the Tamaulipas limestone, which produces oil in the northern fields. Upper Cretaceous limestone and shale, according to the author, rests conformably on the Tamaulipas and are disconformable in most places on the El Abra. Evidence, however, has been presented by M. P.

White indicating a disconformity also between the Tamaulipas and the Upper Cretaceous on the structural "highs" of the northern fields. The Upper Cretaceous section begins with thin-bedded limestones and shales at its base, passing into shales above and sandstones at the top. Transition beds between the Cretaceous and Eocene, belonging to the Tamesí formation, are of Danian (?) age. A hiatus at the base of the Tamesí separates it from the Méndez shale. The very incomplete Tertiary sequence, marked by several disconformities, includes Eocene, Lower and Middle Oligocene, and Lower Miocene strata—mostly clays and shales. Sandstones occur at the base, in the Chicontepec group, and at the top, in the Túxpan formation. Shell limestone and alluvium near the coast are referred to the Pleistocene and Recent.

Figure 13, a composite map of Mesozoic seas, is accompanied by a summary of Mesozoic paleogeography. Thousands of seepages are present in the central Coastal Plain area, within or near the oil fields. Basaltic rocks of Cretaceous and Tertiary age occur as dikes, plugs, sills, and flows.

The structure of the region is the end result of earth movements at several periods, the most intense of which took place during the Eocene when the Sierra Madre region was plicated. The northern oil fields lying west of Tampico are on the southward plunging end of the Sierra Tamaulipas anticline. The southern oil fields, to the west and northwest of Túxpan, are on a buried arcuate ridge whose southern part trends northwest and whose northern part trends northeast. Figure 22 is a structure map of the northern fields contoured on the Tamaulipas limestone; Figure 32 is a structure map of the Southfields contoured on the El Abra limestone. More detailed maps show the structure of many of the individual pools.

Producing horizons in the northern oil fields are the Tamaulipas, Agua Nueva, and San Felipe limestones, made porous by faulting, fissuring, and jointing. Production through December 31, 1934, was 705,800,000 barrels. Four thousand, two hundred, and fifty-four wells had been drilled, of which 1,583 were productive.

The producing horizon in the Southfields is the El Abra limestone, whose porosity is chiefly due to hollow casts of fossils. In an area of about 24,700 acres, 1,002 wells had been drilled up to, and including, December, 1934, of which 523 were productive. The average production was about 40,000 barrels per acre.

At the end of the book are: (1) an Appendix which assembles ten pages of miscellaneous data from the wells; (2) a Bibliography of Mexican oil fields listing two hundred and twelve references; (3) a list of six refer-

ence maps; and (4) a Gazetteer giving the location of places referred to in the text but not shown or easily located on the text figures.

On pages 11 and 16 reference is made to the collection of Upper Jurassic fossils made by W. H. Hegwein in the Sierra San Carlos. These fossils came, however, from the Sierra de Cruillas about 1.8 miles south-southwest of the town of Cruillas. The reviewer has a copy of Hegwein's map showing the location of his fossil localities in the Sierra San Carlos and the Sierra de Cruillas. The Sierra de Cruillas is a distinct physiographic and structural unit at the eastern end of the Sierra San Carlos. The single locality where the Upper Jurassic ammonites were found is in the Sierra de Cruillas, while all the Neocomian fossil localities are in the eastern part of the Sierra San Carlos five to six miles west-northwest of Cruillas on another structural uplift.

On page 155 the last sentence of the fourth paragraph reads: "In the sector south of the Río Túxpan there is an absence of both seepages and intrusions." L. J. Ridings has questioned this statement and lists a number of localities south of Río Túxpan where he has seen seepages and intrusions.

Referring to the Sierra Madre Oriental, the statement is made on page 159: "The pressure that caused the folding came from the west; the observations given indicate a lessening of intensity eastward." The reviewer has studied the front ranges of the Sierra Madre in the area referred to and believes the apparent lessening of intensity eastward is due to release of pressure by overthrusting in the Sierra del Abra and probably in the Sierra de Nicolás Perez.

Geology of the Tampico Region, Mexico, shows the great amount of time and effort invested in it. The author has assembled in usable form the detailed studies made by many geologists over many years, and has added much of his own that is new. He has thereby rendered a great service to the geological profession and to the petroleum industry.

L. B. KELLUM

Devonian Stromatoporoids of North America. By W. A. PARKS. ("University of Toronto Studies," Vol. XXXIX, Part I.) Toronto: University of Toronto Press, 1936. Pp. 125; pls. 19. $1.00.

This paper is a result of an attempt on the part of Professor Parks begun many years ago to name and arrange the great collection of Devonian stromatoporoids in the Toronto Museum. In the progress of the work naturally many new species were found, and the usual great difficulties involved in the study of any large group of extinct animals were

encountered. Stromatoporoid species show great variability, the early descriptions were entirely inadequate, and there has been an amazing lack of agreement not only as to the validity of the classification used but even as to the stromatoporoid position in the animal kingdom. As a consequence Professor Parks was finally led to the ambitious project of describing all the known forms and attempting a revision of the classification. But after many years of study much of the laboratory work was still to be done, and final conclusions as to classification had not yet been reached. Therefore, it was decided that, regardless of the logic of the order, the separate parts of the work were to be published when finished. Thus Part I came to include the introduction and descriptions of genera and species in which the fiber is not reticulate or spongy, that is, the "Hydractinoid" division of Nicholson. Part II was to include a description of the species with reticulate fiber; and Part III was to contain the conclusions as to the nature and relationships of stromatoporoids, together with a Bibliography of North American Devonian forms.

In the present paper no definite taxonomic arrangement is attempted, for Professor Parks's studies of stromatoporoids had convinced him that a complete new classification was required. Unfortunately, Professor Parks's illness made it impossible for him even to complete the final editing of this part of his monograph. We are, therefore, indebted to Miss Alison Ewart and Dr. J. C. Sproule for seeing Part I through the press. Since Dr. Parks died on October 3, 1936, what will become of his even more significant unpublished work on the stromatoporoids remains a question. It is to be hoped that others will see that finally it is printed.

The present paper describes fifteen species of *Clathrodictyon*, of which nine species or varieties are new. Three new genera are also proposed: *Anastylostroma*, *Trupetostroma*, and *Stictostroma*. One new species is described under *Anastylostroma;* three of the eight species of *Trupetostroma* are new; and four of the six species of *Stictostroma* are also described for the first time. The well-known genus *Stromatoporella* is represented by seven species of which two are new, the genus *Actinodictyon* by one new species, and the genus *Actinostroma* by two.

The descriptions are given in detail, and all the species are amply and carefully illustrated.

CAREY CRONEIS

Tertiary Faunas: A Textbook for Oil Field Paleontologists and Students of Geology, Vol. I: *The Composition of Tertiary Faunas*. By A. MORLEY DAVIES. London: Thomas Murby & Co., 1935. Pp. 408; figs. 565. 22*s*. 6*d*.

The issuance of the present volume represents the completion of many years of labor by Dr. Davies, the second volume of his *Tertiary*

Faunas having slipped through the presses, paradoxically enough, in 1934, while Volume I was being delayed owing to the large number of illustrations which had to be prepared for it.

Dr. Davies states in his Preface:

> In the troublesome matter of nomenclature I make no claim to authority. I have tried to place before my readers the alternative generic names . . . . and I have had in each case to show one name as the most correct and enclose the rest within square brackets. In these concentration camps are herded together many that will suffer the death penalty (synonyms), some doomed to banishment (homonyms), some that may be set free and acclaimed as the long lost heir, and yet others that may be allowed to live as poor relations (subgenera). I have tried not to be too arbitrary a dictator in my choice of victims, though I am sure to be criticized. . . . .

It might be supposed a priori that any writer who could pen a statement such as the foregoing might be expected to turn out an exemplary work on Tertiary faunas, and in such anticipation most readers will not be disappointed. The work, however, is *not* a systematic paleontology of the Tertiary, since practically all the emphasis is placed on four groups only: the Foraminifera, the Echinoidea, the Pelecypoda, and the Gastropoda. All the other invertebrates, and the vertebrate division as well, receive such scant attention that one might well wonder why they were included at all. But the four favored groups are voluminously treated. Each chapter begins with a statement regarding the structure of the skeleton and definitions of the technical terms employed. Ontogeny and habits are also discussed when these features are of importance to the paleontologist. The classifications employed are outlined and compared with others in common use. Then there is given a systematic description of the families and genera, and the ranges of the latter are indicated both as to time and as to space. Each section has not only a well-selected Bibliography but a very valuable Glossary, and for a few of the groups evolutionary outlines are also included. The illustrations, almost entirely the work of Mrs. Davies, are somewhat diagrammatic but effective. The book is replete with these line drawings, seventy-one whole-page plates being included.

In his treatment of the Foraminifera, Dr. Davies gives a comparison of three well-known classifications: Brady's, of 1884, and Cushman's and Galloway's, both of 1933. Since he regards the latter classifications not only as tentative but as presenting a forbidding complexity to the student, he patriotically retains the ancient British scheme, although admitting in the same breath that the new classifications express the evolutionary relationships of the genera much better than does Brady's.

Some idea of the scope of this volume and the amount of work involved in its preparation may be gleaned from the fact that approximately sixteen hundred animal groups were dealt with. Moreover, most of the diagnoses given for these groups seem to be accurate. Doubtless, therefore, the work will have a considerable usage in North America as well as in Europe.

CAREY CRONEIS

Procedure in Taxonomy. By EDWARD T. SCHENK and JOHN H. MCMASTERS. Stanford University, Calif.: Stanford University Press, 1936. Pp. 72. $2.00.

Here is just the book which has long been needed by every professional paleontologist and zoölogist. Furthermore, it is suitable as a supplementary text for all advanced courses in which taxonomy of necessity plays a role. In it the originally obscurely published International Rules of Zoölogical Nomenclature are reprinted in full. In addition, it contains the summaries of the first 123 opinions handed down by the International Zoölogical Congress. Unfortunately, the volume appeared a little too early to include the last set of opinions rendered, namely, 124 to 133. These were published as No. 8, Volume LXXIII, *Smithsonian Miscellaneous Collections*, dated October 28, 1936. Thus *Procedure in Taxonomy*, in conjunction with the afore-mentioned Smithsonian publication, will bring to the hands of workers in taxonomy most of the information necessary for accurate work.

For many years proper procedure in taxonomy has been the exception rather than the rule, so that students quite generally have come to feel that taxonomy is not only a bugbear but an actual enemy of research in zoölogy and paleontology. An ordinary case in point will show that this attitude is not without sound foundation. In 1866 R. Ludwig described fifty-six new genera of Paleozoic corals. Six years later P. Martin Duncan wrote, "Ludwig has added to the confusion by not acknowledging the [present] classification in the least; and in his enthusiasm (anti-Gallican enough) he alters generic and specific names, employs sesquipedalian Greek, and absorbs original authors." As a result of Ludwig's taxonomic shortcomings later workers have refused to recognize *any* of his generic names although some clearly have priority over those now in use. In fact, the taxonomic situation has become nearly as bad as F. A. Bather once predicted, namely, that scientists would soon be describing each new form as follows, "A charming species, rather large. Number 56xyz." The present publication indicates clearly the course to be taken in avoid-

ing all the common taxonomic pitfalls, and as a consequence the authors are to be congratulated for their service.

Procedure in Taxonomy is the result of long-continued serious collective deliberation. This was begun in 1931 as a symposium of graduate students and professors at Stanford University. As a result of the conferences of this group a report was prepared in mimeograph in 1932. The demand for this work was so widespread that the symposium was enlarged and continued through 1935, at which time the original text was revised and brought into its present form. The volume is divided into eight chapters. The first, or Introduction, discussed binomial nomenclature. The second defines the systematical divisions of the animal kingdom. The third deals with types and recommends a reduction of the number of kinds of types. Chapter iv gives rules for the description of new species, which, if followed, will make comparisons simpler in the future. Chapters v and vi deal with the problems of specific names and synonomy. Chapters vii and viii have to do with storage of type material and Latin terms and abbreviations. The Appendix, which comprises the major portion of the volume, includes the International Rules and the Summaries of Opinions thus far rendered. The book is completely indexed, but it lacks the bibliographic references which would have further enhanced its value.

CAREY CRONEIS

Klockmann's Lehrbuch der Mineralogie. By PAUL RAMDOHR. Stuttgart: F. Enke, 1936. Pp. 625+xii; figs. 613. Rm. 34.00 (unbound), 36.80 (bound); less 25 per cent outside of Germany and Switzerland.

This textbook by Ramdohr's former colleague at Aachen now appears in its eleventh edition, though recent editions since 1912 have not been greatly changed. The new work is 42 pages shorter than the 9/10th edition, in addition to which the 41-page "Tabellarische Übersicht" is omitted. Although a new 19-page section on X-ray crystallography is introduced, the section on morphology is 36 pages briefer; that on physical mineralogy 30 pages. There are only minor changes in the lengths of the other subdivisions, descriptive mineralogy, for example, being allotted 315 pages to 326 in the last edition. In this section haloids are introduced earlier (after oxides, which include the spinellids), and silicates are given in the order of Bragg's classification as extended by Schiebold.

The new division on X-ray work devotes three sections (9 pages) to an attempt to explain experimental and interpretative methods, two (6 pages) to lattice types and ionic radii, and one ($3\frac{1}{2}$ pages) to silicate struc-

tures, part of which last is repeated later under silicates where all of it belongs. Such brief treatment to the subjects of the first three sections could as well be omitted, and certainly the next two sections belong with isomorphism.

Perhaps the best feature of Klockmann is the attention paid to genesis, both in a special 40-page introductory section and in the descriptive part of the work. In this edition Ramdohr is probably most effective in bringing this field up to date. The revisor's special interest is also shown by the introduction of R (reflecting power) or κ (index of absorption) values for certain ore minerals.

Much effort was expended in correcting the descriptive part of the work. Space-lattice data are given. The structure type is indicated in some cases; in a few others tiny diagrams are printed. Where unit cell dimensions do not accord with axial ratio, the latter is generally left unchanged, apparently after due consideration. An extreme case of this is treating wollastonite as monoclinic but putting it under the triclinic pyroxenes. Titles for the figures are lacking. Diagrams or other data correlating optical properties with chemical composition are rare. The Index lacks such items as Gauss (p. 37) and *Metamikt* (p. 222). The disthene of page 504 is kyanite on pages 485 and 499, and the *Kieselzinkerz* of page 510 is hemimorphite on page 509. The book lacks determinative tables, though blowpipe and microchemical tests for the elements are listed. Abbreviations listed on page 290 are not uncommon earlier in the work. A worth-while feature is the list (7 pages) of superseded or doubtful mineral names. The work is, on the whole, both modern and excellent.

D. JEROME FISHER

"Geomorphology of the North Flank of the Uinta Mountains." By W. H. BRADLEY. *U.S. Geological Survey Professional Paper 185-I.* Washington: U.S. Geol. Surv., 1936. Pp. 35; figs. 14; pls. 12; price $0.45.

In a careful analysis of the major geomorphic features of this interesting area Bradley finds evidence of two major erosion surfaces or pediments, developed after the Eocene epoch but before the late Pliocene, and partly buried respectively by the Bishop conglomerate and the Browns Park sandstone and tuff.

The oldest or Gilbert Peak surface once included all but the highest portions of the range. Sloping northward and northeastward from residuals that stood 1,000 feet or more above it, this surface bevels all formations from the pre-Cambrian Uinta Mountain series in the core of the range to the Eocene Green River formation in the basin on the north. Its age is

thought to be Oligocene or Miocene. In Bradley's longest and most perfect profile, the slope of this surface ranges from 400 feet per mile near the Uinta crest line to 55 feet per mile at a distance 35 miles north of the crest. Thus the Gilbert Peak remnants fit into a surface of concave slope, which is buried to a maximum depth of 200 feet in its central part by the Bishop boulder conglomerate. Characteristics of both the slope and the Bishop conglomerate point to arid conditions during their formation—thus the Gilbert Peak surface must be regarded as a pediment. This surface appears to correlate with the Wind River peneplain, the summit erosion surfaces in the Bighorn and Medicine Bow ranges, and possibly with Mansfield's Snowdrift peneplain in southeastern Idaho.

The second or Bear Mountain surface appears also to have been a pediment developed under arid or semi-arid climate. Its remnants are best preserved in the central and eastern parts of the range, and lie approximately 500 feet below the Gilbert Peak level. At the west the Bear Mountain surface appears to correlate with the Bridger and Cottonwood benches, now thinly veneered with gravel interpreted as the basal conglomerate of the Browns Park formation. The latter formation is extensively preserved in Browns Park valley on the northeast flank of the range. Here the Bear Mountain surface is buried under 1,200 feet of fine sandstone and glass tuff overlying a basal conglomerate. Suggestive though not conclusive evidence points toward an eolian origin and an Upper Miocene or Lower Pliocene age.

Drainage from both the Gilbert Peak and the Bear Mountain surfaces led northeastward to a tributary of the Platte River. Conditions were abruptly changed by a collapse of the east end of the Uinta arch. The displacement of the older erosion surfaces where faulted or tilted is used by Bradley in calculating the amount of movement. In the graben thus formed, the Green River and other streams, which formerly flowed eastward, were diverted southward around the east end of the range. Somewhat later the Green River gained its present Lodore Canyon through the range, probably by piracy by a small tributary of the Yampa River on the south slope of the Uintas.

Geomorphic features of Pleistocene age, not mapped in detail by Bradley, include moraines of three ages and two sets of benches or stream terraces. The latter are the Tipperary bench, some 150 feet below the Bear Mountain level, and the Lyman bench 50–75 feet below the Tipperary. Neither progressed beyond the strath stage of development. Bradley believes that they were formed during the relatively dry interglacial stages, and were trenched during moist glaciations.

The three glacial stages are Little Dry (oldest), Blacks Fork, and Smith Fork (youngest). These appear to correlate respectively with Blackwelder's Buffalo, Bull Lake, and Pinedale stages in the Wind River Range, and with the Cerro, Durango, and Wisconsin stages of Atwood and Mather in the San Juans. Gilbert's First and Second Bonneville stages of high water and glaciation in the Wasatch region probably correspond to the Blacks Fork and Smith Fork stages here.

W. E. POWERS

Rutley's Elements of Mineralogy. By H. H. READ. 23d ed. London: T. Murby & Co., 1936. Pp. viii+490; figs. 128. 8*s.* net.

This new edition carries ninety-six more pages than the last (1929); crystallography is increased by twenty-nine, optics by twenty-two, and descriptive mineralogy by thirty pages; and a new twenty-page chapter on occurrence is introduced, though this incorporates the glossary of older editions. The whole book has been reset. Minerals are classified according to positive elements in order of the groups of the periodic table. Silicates are described in eighty-seven pages; they are arranged "in the more or less natural families in which they occur in the rocks." The X-ray classification is ignored, and isomorphism is treated in less than a page. The conservative character of the book is indicated by statements like the following: "Theoretically, all molecules of a mineral must be identical"; "a mineral is a substance having a definite chemical composition . . . ." (though this is qualified in the earlier discussion); "Crystals are bodies bounded by surfaces, usually flat, ..." But in terms of "good old-fashioned mineralogy" the book certainly offers a lot for the money, and its long-lasting success indicates that the revised edition will fill an important need.

D. JEROME FISHER

Mineralogy. By E. H. KRAUS, W. F. HUNT, and L. S. RAMSDELL. 3d ed. New York: McGraw-Hill Book Co., 1936. Pp. ix+638; figs. 812. $5.00.

The third edition of this well-known book is fundamentally the same in plan and content as the two earlier editions by Kraus and Hunt that preceded it (the first edition was reviewed in the *Journal of Geology*, Vol. XXI [1921], p. 188). Sixty-six new illustrations have been added and the number of pages has been increased by thirty-four.

Changes have been slight, but the most notable are the addition of new material in the chapter on crystal structure and X-ray analysis, inclusion of some data on the structure of the silicates, revision of statis-

tics on mineral production in the chapter on classification of the minerals according to the elements. Very minor changes have been made in the chapters on the polarizing microscope, physical properties, and formation and occurrence of minerals.

The many halftone illustrations of the crystal models and mineral specimens, a unique feature of this book, are retained. Many of them (as, e.g., Figs. 684 and 742) are notably less clear in the third edition than they were in the first.

F. J. PETTIJOHN

Treasures in the Earth. By E. F. FITZHUGH. Caldwell, Idaho: Caxton Printers, 1936. Pp. xii+131; pls. 16. $2.00.

In this popular account of engineering and mining geology the author makes a distinct contribution to popularized scientific literature. After a brief historical Introduction, Mr. Fitzhugh introduces his readers to the processes of geology, from magmatic intrusion to final exposure of the batholith by later erosion. Next the author describes the magmatic juices that escape from the intrusion, and their role in forming ore deposits. Following these considerations the reader is introduced to the sequence of ores resulting from the gradual cooling of the magmatic liquids as they penetrate the surrounding rocks. The characteristics of such deposits are described, and typical mines are used as examples. Changes that occur in the zone of oxidation are also described, and finally the subject of placers is considered.

In order to introduce the reader to some of the complexities of actual mining practice, Mr. Fitzhugh includes a chapter on structures, and illustrates the complexities of successive faulting in an ingenious manner. The volume closes with a brief consideration of modern methods of ore prospecting.

This handy volume will be of interest to the general educated reader, and it is adaptable for supplementary reading in an introductory course in geology, inasmuch as it affords material not usually included in general courses. The style and organization of the book are excellent, and the illustrations are well reproduced.

W. C. KRUMBEIN

Das Sonnwendgebirge im Unterinntal: Ein Typus alpinen Gebirgsbaues. By FRANZ WÄHNER. Leipzig and Vienna: Franz Deuticke, 1935. Part II. Pp. xvi+200; figs. 10, pls. 30, including a geological map in rear pocket. Rm. 40.

The present volume is the second part of Dr. Wähner's important work in the Sonnwendgebirge. The first part of the study appeared in 1903,

and comprised a survey of the earlier literature, a review of the stratigraphy, and a tectonic consideration of the eastern half of the range. The second part, described here, includes a detailed discussion of the larger western part of the mountains, and a geological map of the entire region.

The Sonnwendgebirge lie in the eastern and northern part of the Alps, adjoining the Achen See. Dr. Wähner describes the several peaks and intervening areas in considerable detail, with running descriptions of the stratigraphy and details of the rock formations.

The main points of the work are well illustrated by a series of about forty photographs, some panoramic, with lines superimposed on the photographs to differentiate important formations. The geological map, on a scale of 1:10,000, adequately shows the details of stratigraphy and structure.

W. C. KRUMBEIN

Atlas for the Geology of Szechuan Province and Eastern Sikang. Memoir of the Geological Survey of China, Ser. A, No. 15. By H. C. TANN and C. Y. LEE. Peiping: National Geological Survey of China and Institute of Geology of the National Academy of Peiping.

An atlas of Szechuan containing thirty-eight large-scale geologic maps, one index map, six cross sections, and five columnar sections based on well logs has been released in advance of the text in preparation which will supplement it. Together they will constitute a geologic study of the largest province of China. The province is made up principally of the Liangshan Range of the eastern Tibetan fault-zone on its western margin and the very broad Red Basin, cut by four main rivers draining into the Yangtze Kiang which borders Szechuan on the southeast. Paleozoic sediments continued to be deposited in a gulf of the sea which remained in the Red Basin after the north Mongolian region had become land. Freshwater deposits continued through the Mesozoic.

The salt region and oil fields of Tzuliuching and Kungching are mapped on a special, large map as is the coal region of Wanhsien, Tahsien, and Liangshanhsien. All maps contain the outstanding cultural features and drainage patterns; only the map of the salt region has contours (interval, 25 m.). The province is, in general, mapped only along the rivers. The major part of the upland is unmapped.

JEAN GRACE

La Géologie et les mines des vieilles plateformes. By F. BLONDEL. Paris: Société d'Editions Géographiques, Maritimes et Coloniales, 1936. Pp. 303; figs. 29.

In this work, M. Blondel, engineer-in-chief of French mines, has attempted to further the understanding of the major tectonic arrangements

of the continents by a study of the minerals which the different geologic units contain. On the other hand he has, in Part II, described the mineral occurrences in terms of a system of classification of geological regions, based on a conception of crystal history and structure which he presented and exemplified in Part I.

Blondel's *vieille plateforme* is a relatively rigid and stable continental area, which has remained so since the beginning of the Cambrian. The ancient platforms consist, then, of all our pre-Cambrian shields and their rigid extensions beneath later horizontal sediments. The platforms of the world are considered to consist of two units, the "basic series" and the "covering series." The former is subdivided into the "crystalline pedestal" and the "semi-metamorphic series." In the discussion of these subdivisions, interesting problems of intrusive relations and metamorphism are oriented within his concept.

Belts of folded post-Proterozoic rocks are either intraplatform exceptions to the stability or comprise the *zones plastiques* of the earth. The two types of folding are distinguishable by their position and by their history. The rigid zones tend always to grow at the expense of the plastic zones which border them and which, once folded, appear to become stable adjuncts of the platforms. This tendency is illustrated by the migrating zones of folding of the Hercynian and later Alpine disturbances.

The geological problems, types, and histories of the rigid zones differ notably from those of the plastic zones which have, however, been the areas in which geology has had its beginnings and greatest development as a science, and the patterns of which have been too often carried over in the interpretation of dissimilar areas. The regional geology of all the major areas of pre-Cambrian outcrop or of horizontal post-Proterozoic strata is briefly summarized in support and instance of the author's views.

The second and slightly longer part of the book deals with minerals and mineral groups, correlating their order of abundance for a given area and kind of rock, not only, as is customary, with the nature of the mineral, but with the tectonic history of its environment. The relative stability of the platform is a factor of particular importance for minerals whose source is in the *vieilles plateformes*.

The discussions in this book, which is primarily a general work of geological philosophy, are such as to be of interest and intelligible to all classes of geologists, to geographers, and to laymen interested in geology or in mineral resources.

JEAN GRACE

Asia: A Regional and Economic Geography. By L. DUDLEY STAMP. (Rev. ed.) New York: E. P. Dutton & Co., Inc., 1935. Pp. xxi+704; figs. 350. $8.00.

Six years ago the first edition of an economic and regional geography of Asia by L. D. Stamp appeared; eighteen months later a second edition was published. Changing conditions in Asia, a changed demand due to the shift of interest of non-Asiatic peoples, the availabliity of new, more detailed regional studies, and Dr. Stamp's own further research in some regions have warranted this revised edition.

Throughout, the geographical material is interesting to natural scientists of all classes. Sections on the geography of each region are prefaced by factual accounts of the regional geology. However, it is in the first two chapters that the author has concentrated most of his larger geological facts. The first chapter, "The Orography of Asia," is a clear, brief, and integrated presentation of the morphology of "Asia the Mountain-hearted." The chapter on the geologic structure is remarkable for treating in a very few pages a large number of the theories which, although more widely held in Europe, are generally considered as untenable by American geologists.

JEAN GRACE

The Welsh Borderland. By R. W. POCOCK and T. H. WHITEHEAD. "British Regional Geology." London: H. M. Stationery Office, 1936. Pp. 84; figs. 39; pls. 11. *1s. 6d.*

From England comes this study of the famous area which is so generally associated with such names as Murchison, Sedgwick, and Lapworth. This bulletin treats concisely the general geology of the Welsh borderland, incorporating the results of recent work in the classic localities for the Cambrian, Ordovician, and Silurian.

The topography, drainage, and physiographic history are described in brief, followed by a more extended discussion of the stratigraphy, structure, and igneous history of both the pre-Cambrian and Paleozoic sequences of the area. Considerable attention is given to the structual conditions, with numerous maps and charts. Characteristic fossils of the Paleozoic formations are illustrated. Not the least interesting is the section devoted to the Coal Measures and the Permian rocks. No hard-rock formation younger than the Kemper marl of the Upper Triassic now occurs in the district. The final chapter is devoted to the glacial and other superficial deposits.

DAN J. JONES